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VELOCITY PROFILE CHARACTERIZATION FOR THE 5-CM AGENT FATE WIND TUNNELS

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14. ABSTRACT
This report describes the velocity profile characterization of the 5-cm Agent Fate Wind Tunnel. This facility, which fits in a standard chemical fume hood, is used to measure the release and retention of chemical warfare agents from various materials under simulated environmental conditions. The tunnel creates specified vertical velocity profiles representing the lower portion of the velocity profile produced by a wind-induced, atmospheric boundary layer. Characterization refers to the measurement of the velocity profiles over the length and width of the test section under various test conditions. The report summarizes the instrumentation employed, the characterization procedure, and resulting velocity profiles measured in the Version 3 and Version 3, Mod 1 configurations of the 5-cm Wind Tunnel as employed for the HD on glass (tunnel validation) and the HD on sand test phases of the Agent Fate Program.

15. SUBJECT TERMS

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PREFACE

The work described in this report was authorized under Program Element No. 6R27CZ. This report covers work performed between April 2004 and April 2006.

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VELOCITY PROFILE CHARACTERIZATION FOR THE 5-CM AGENT FATE WIND TUNNELS

1. INTRODUCTION

The Agent Fate Program is sponsored by the Defense Threat Reduction Agency as a Defense Technical Objective: CB.42 - Environmental Fate of Agents.[1] The objective of the program is to measure and understand the physico-chemical processes for Chemical Warfare agents (CWAs) on surfaces in order to predict their persistence and fate in operational scenarios via agent fate models. Of prime interest are the amount of liquid volatized and the residual agent remaining in the substrates under a set of controlled environmental conditions defined by wind speed, temperature, and relative humidity. The resulting experimental data are then used to develop models to predict threat persistence for operational scenarios.

One of the major elements of this program consists of experiments performed in a series of 5-cm Wind Tunnels.[2-4] These facilities, which fit in a standard chemical fume hood, are used to measure the release and retention of CWAs from various materials under simulated environmental conditions. A key feature of this wind tunnel is that it creates specified vertical velocity profiles representing the lower portion of the velocity profile produced by a wind-induced, atmospheric boundary layer. The attention to duplicating the detailed velocity profile over the drop/substrate was one of the main features that set this experimental arrangement apart from previous agent fate type studies. It is important that these velocity profiles be characterized in order to validate and interpret the subsequent experimental data obtained in the 5-cm Wind Tunnel, as well as, to allow comparison with the velocity profiles present in other different sized wind tunnels supporting the Agent Fate program. Characterization, as used here, refers to the measurement of the velocity profiles over the length and width of the test section under various test conditions. This report summarizes the instrumentation employed, the characterization procedure and resulting velocity profiles measured in the Version 3 and Version 3, Mod 1 configurations of the 5-cm Wind Tunnel. These tunnel configurations were used for the HD on glass (tunnel validation) and the HD on sand test phases of the Agent Fate Program.[5]

2. BACKGROUND

The Agent Fate Wind Tunnel studies are intended to provide data to the modelers on the fate sequence of agent drops on different substrates under the combined influence of wind, temperature, and humidity. Figure 1 describes the overall fate of agent deposited on a substrate and illustrates the sequence of events in terms of the agent vapor and agent mass being measured in the wind tunnels. The figure does not contain actual experimental data, but is intended to illustrate the types of data obtained in the wind tunnel test.

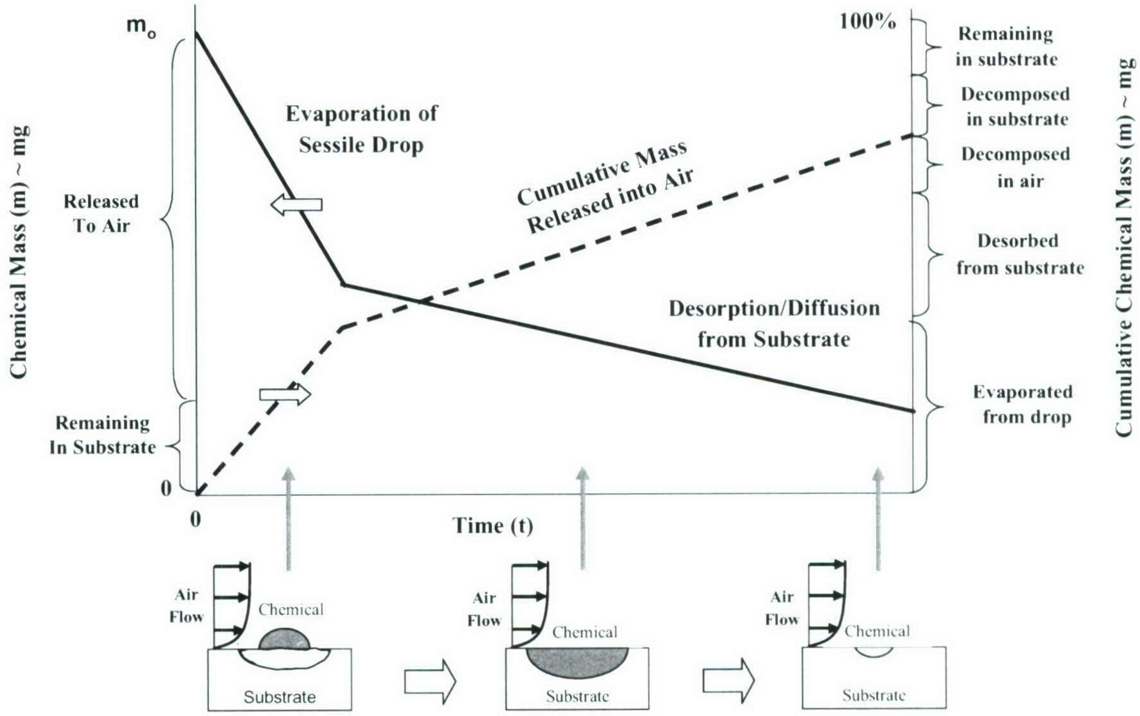


Figure 1. Agent Fate Sequence

For the case shown in the figure, the substrate is both sorptive and reactive. At the start of the test, a drop or drops of agent are deposited on a substrate specimen. A portion of the agent forms a sessile drop on the surface while the remainder is sorbed into the substrate. The substrate sample is then inserted into the floor of the wind tunnel test section. The wind tunnel air flow is then established for the desired specific velocity, temperature, and relative humidity conditions. The chemical volatilizes into the air passing over the substrate with the resulting vapor carried away by the air stream. As time passes, the sessile drop on the surface completely volatilizes leaving only the chemical sorbed in the substrate which also begins to desorb. This phase exhibits a markedly lower volatilization rate than was the case for the sessile drop. Testing continues until no vapor appears to be released from the substrate. This may range from minutes to weeks depending on the chemical, substrate material, drop size, velocity, temperature, and relative humidity.

Throughout this operation, the agent vapor and air mixture are analyzed by means of an on-line, Thermal Desorption Gas Chromatography - Mass Spectrometer (TD-GC-MS) system and/or by sorbent tubes to determine the agent vapor mass concentration released as a function of time. The amount of agent released into the air represents important data for the model development because it represents the initial conditions for transport and diffusion models. These models predict the movement of the vapor cloud under the influence of wind

over the terrain. The TD-GC-MS can also be used to determine whether any of the agent decomposes in the air. After the test, the substrate can be analyzed for any residual chemical or chemical decomposition products by means of various analytical methods including spectroscopy (e.g., *in situ* NMR), extraction followed by chromatographic analysis or other methods. In this way, the fate of the chemical from each of these mechanisms can be determined for the experimental conditions evaluated. Any chemical remaining in the substrate is also a major concern to model development because it may represent a contact hazard or be released at a future time due to surface displacement, rain, or other effects.

3. 5-CM WIND TUNNEL CONFIGURATIONS

3.1 Tunnel Version

The Version 3 Wind Tunnel configuration, shown in Figure 2, is an open circuit arrangement with a "Twisted S" shape layout. Figures 3 and 4 contain schematics of the wind tunnel denoting its major components consisting of a transition cone, turning vane section, fetch, test section, mixing section, static mixer, sampling section and support frame. The tunnel has an overall width of 93.2 cm, an overall height of 56.7 cm, and an overall depth of 55 cm. Figure 5 depicts a cut-away view revealing the internal elements in the turning vane section, fetch, test section and exhaust section.

Except for the nickel coated, plastic transition cone, all tunnel components are fabricated from stainless steel. The fetch, mixing section and exhaust section are made from 5-cm external dimension, square cross-section, stainless steel tubing. While the inside dimension of the tubing is 4.85 cm, the tunnel is referred to as a 5-cm Wind Tunnel. The static mixer and test section are constructed from stainless steel sheet and plate, respectively. Many of the stainless steel components included welded flanges, allowing them to be connected by screws with silicon rubber, chemical resistant, Kalrez R® gasket material in between.

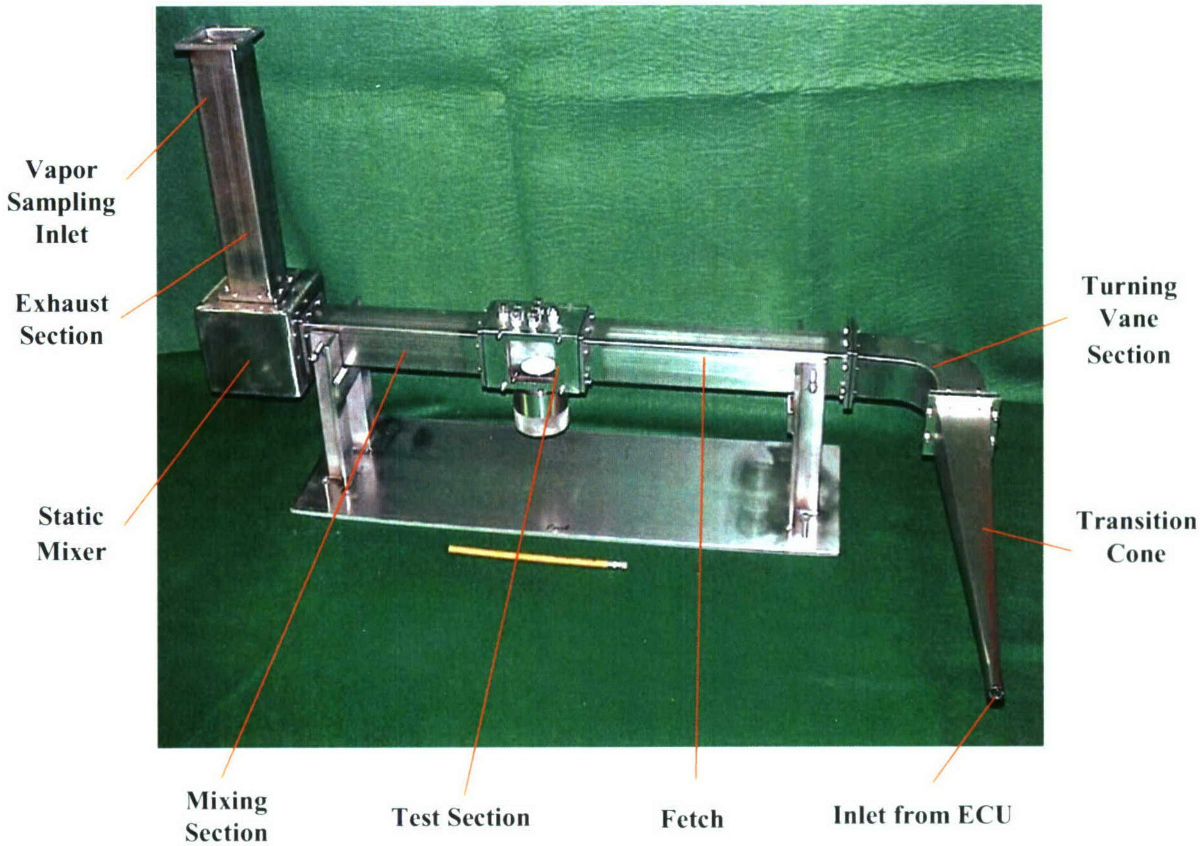


Figure 2. Version 3 (Production) Wind Tunnel

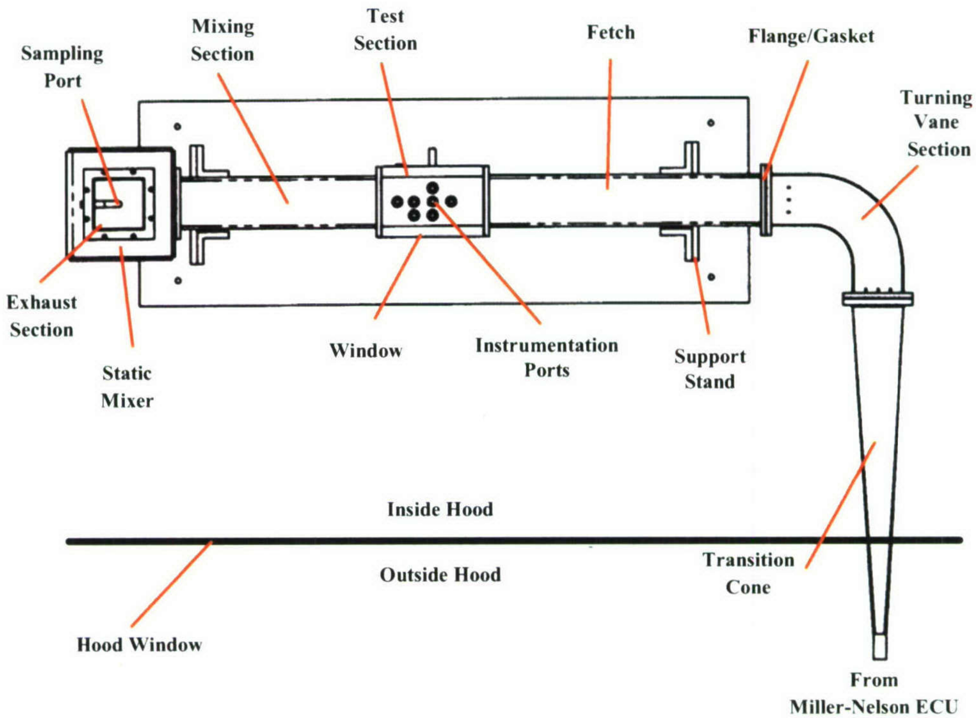


Figure 3. Version 3 (Production) Tunnel Schematic: Top View

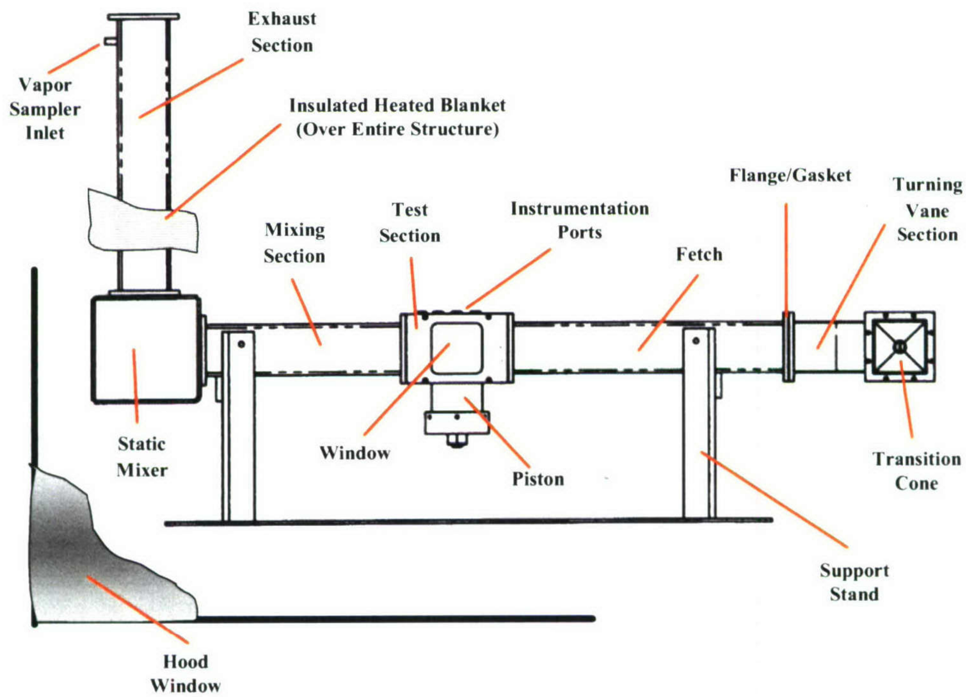


Figure 4. Version 3 (Production) Tunnel Schematic: Front View

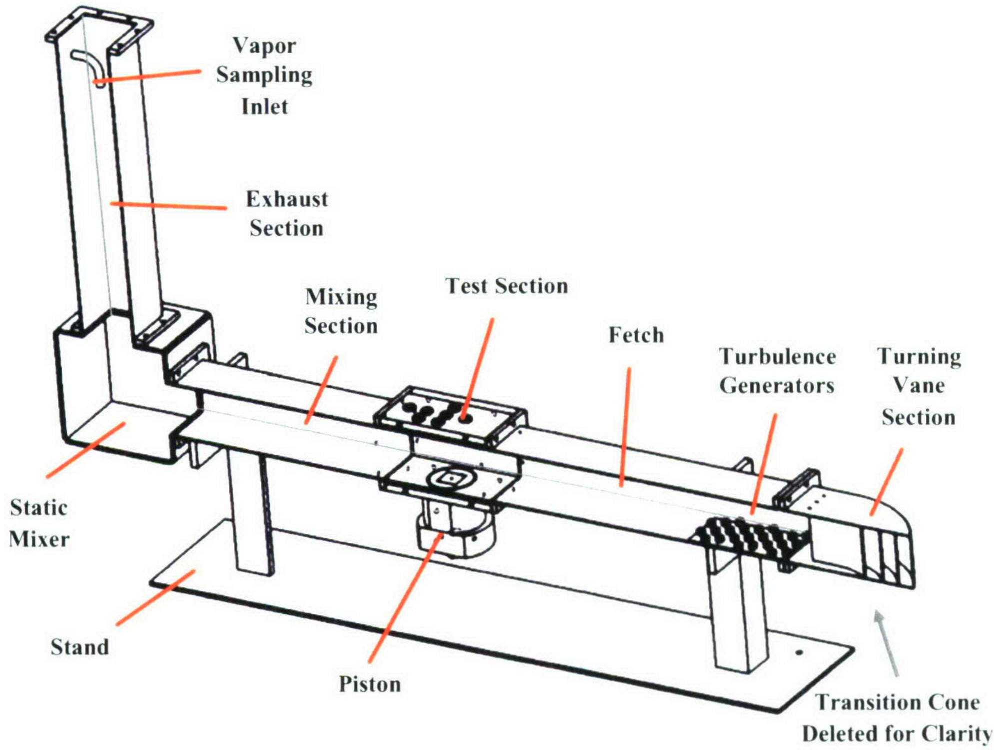


Figure 5. Cut-Away View Showing Internal Elements

A Miller-Nelson Environmental Control Unit (ECU) provided the tunnel air flow at a prescribed temperature and relative humidity. The unit was located in front of the fume hood and supplied air through a 1 cm internal diameter tube into the transition cone. The turning vane section, shown in Figure 6, contains three constant radius vanes that direct the air flow through a 90° bend into the entrance to the fetch. This arrangement resulted in the "twisted S" layout of the tunnel.

The floor of the fetch entrance contains turbulence generators that alter the air flow to create the desired velocity profiles in the test section. These are composed of an ordered array of 23 Teflon cubes (4.8 mm on a side) glued to a flat stainless steel strip glued to the floor of the fetch as shown in Figure 7. Considerable development effort went into evolving this turbulence generator array as discussed in Section 4.2.

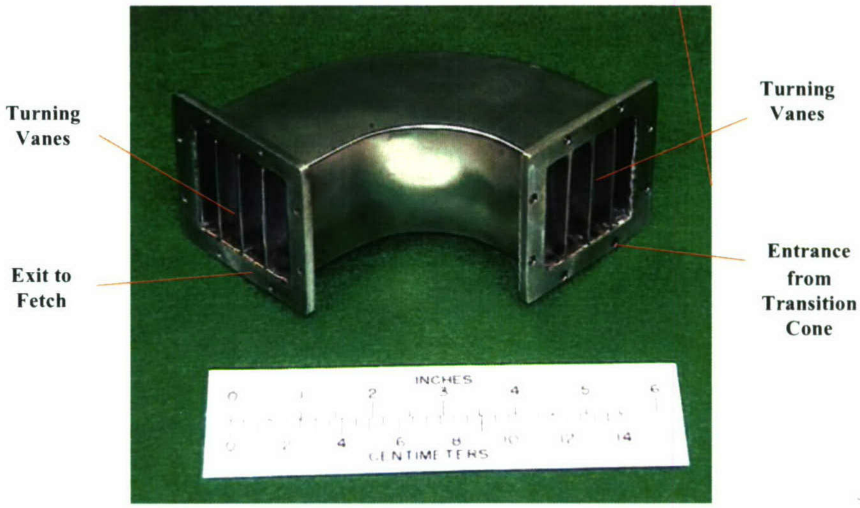


Figure 6. Turning Vane Section

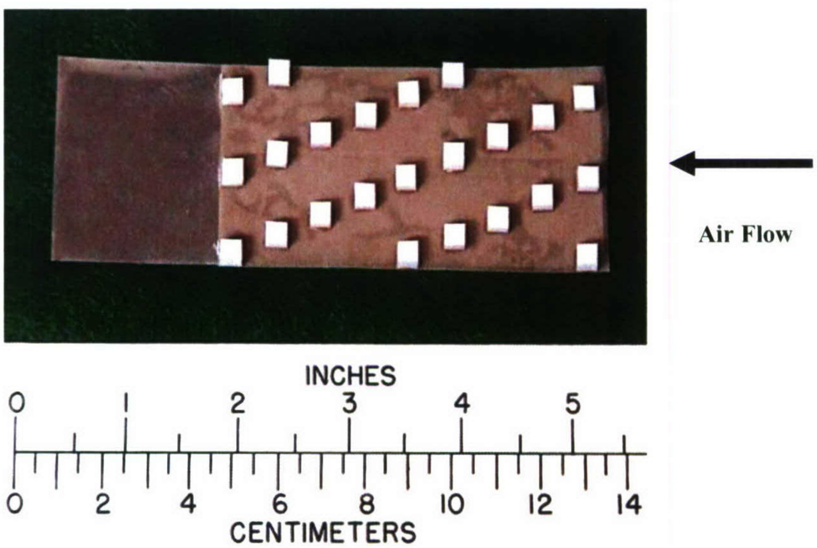


Figure 7. Cubical Turbulence Generators: Top View

The test section, shown in Figure 8, is fabricated from machined stainless steel plates attached by screws. Linear ethylene propylene rubber gaskets (fabricated from cut-up O-rings) provided a seal between the plates interfaces. The test section ceiling contains a total of seven instrument ports. These include an array of five ports for the hot wire anemometer probe: a central location, an upstream and a downstream location, and a left and a right lateral location. All five positions are used for the velocity characterization surveys. The port location downstream of the center position was used for the reference velocity probe during the agent fate experiments. The test section temperature is monitored through the port located most downstream from the center port position. A 4.85 cm^2 flat side window is located on the side of the test section. It is flush with the test section floor to provide an unobstructed side view of the sessile drop of agent on the substrate surface.

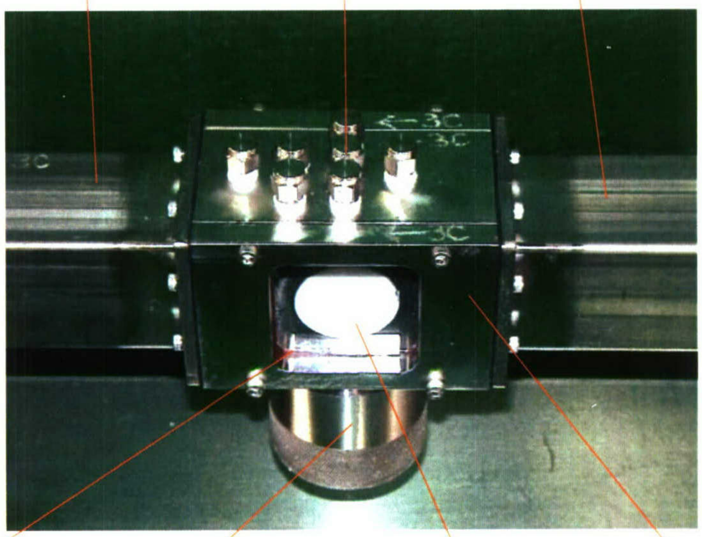


Figure 8. Test Section

Prior to a test, the substrate is placed on the upper surface of a cylindrical piston located in the floor of the test section. The piston, which is composed of a Teflon center section and a stainless steel outer body, is located in the center of the test section floor. The outer body is threaded and is inserted into a threaded hole in the test section floor until the top surface of the substrate is flush with the test section floor. The top surface of the piston measures 3.8 cm in diameter and can contain either a circular or square cavity to hold the substrate sample. The lower portion of the piston's outer body includes a knurled finish to facilitate installation and removal of the piston. A rubber "O" ring is located in a circumferential slot on the outer surface of the piston as a seal between the piston and the test section floor.

The static mixer is a hollow, cubical box having internal dimensions of 10 cm on a side, considerably larger than either the inlet or exit ducts. The air flow from the mixing section enters the mixing box where it circulates and mixes before exiting at a 90° angle into the exhaust duct. The vapor sampling probe consists of a stainless steel tube welded to the exhaust and enters from the side, curving through a 90° bend to face directly into the air flow. The flexible Teflon inlet tubing leading to the sampling instrumentation is inserted into the sampling tube until the leading edges of the flexible tube is flush with the end of the stainless steel tube. This placed the sampling inlet 5 cm upstream from the exit of the exhaust section, on the centerline of the exhaust duct and oriented parallel to the air flow.

The primary vapor sampling instrument is the Versatile Tube Sampler (VTS).[5] The VTS consists of a series of 30 vapor sorbing Depot Area Air Monitoring System (DAAMS) tubes that sequentially collect the vapor/air mixture at the tunnel sample port. After the test, the content of the tubes are analyzed providing a time history of vapor concentration. In order to maintain constant temperature conditions throughout the wind tunnel, its entire structure is enclosed in an insulation/temperature controlled blanket.[5]

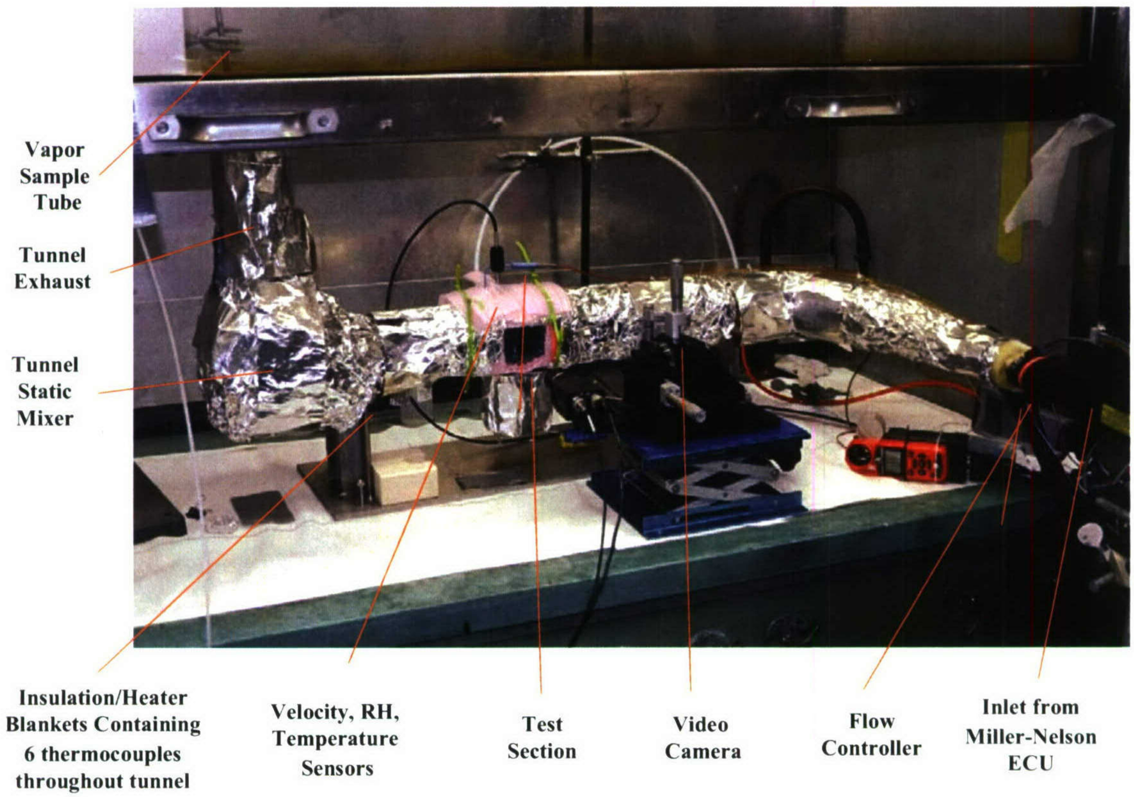


Figure 9. Version 3 Tunnel and Associated Instrumentation[5]

Details of the Version 3 tunnel and its associated instrumentation are depicted in Figure 9. Figure 10 illustrates the tunnel installed in the fume hood along with a person as a size reference.

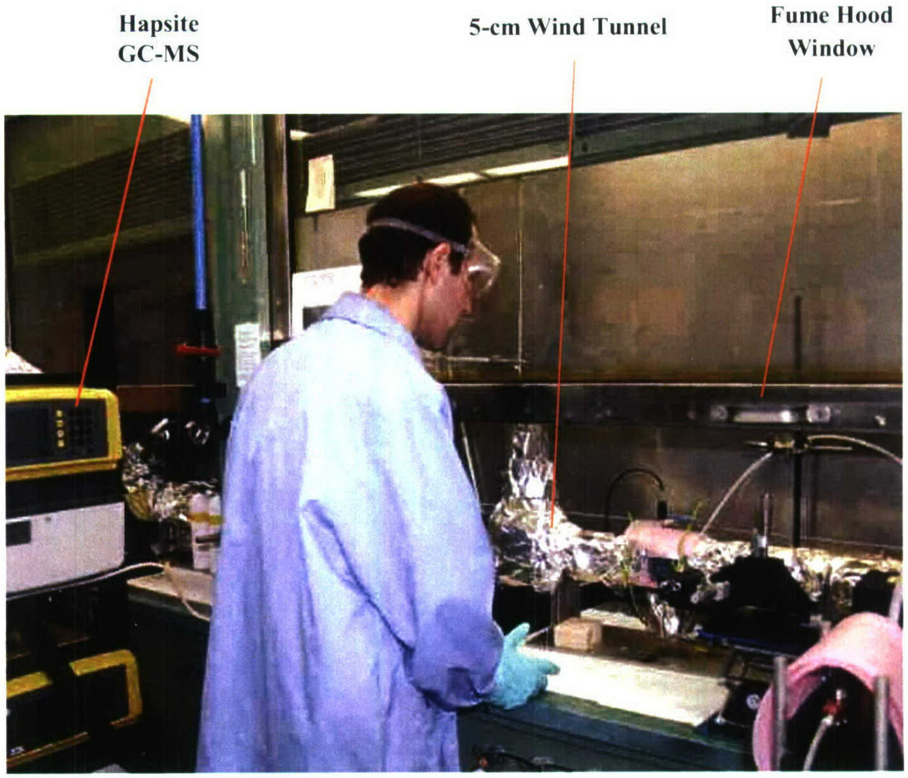


Figure 10. Version 3 Tunnel Installed in Fume Hood

Depending on the desired test temperature conditions, the wind tunnel side walls are either heated or cooled. For the medium and high test temperature, both which are above room temperature, the tunnel is wrapped with electric heating tape. The configuration of a tunnel for low temperature tests require wrapping the upstream sections up to and including the test section with copper tubing through which cold water was circulated. Thermocouples monitored and controlled the tunnel wall temperature which had to remain constant throughout the entire test. Because of the special arrangements required to achieve these two ranges of temperatures, certain tunnels were dedicated for medium and high temperature tests and others for cold temperature tests.[5]

3.2 Tunnel Version 3 Mod 1

The Version 3 Mod 1 tunnels are intended for installation in the large capacity chemical fume hoods. A new support structure was designed allowing a group of four Version 3 tunnels to be installed in a single hood. This arrangement required the humidity and flow control units to be located to the side of the hood permitting the hood sash to be closed during testing operations. In order to accomplish this, the transition cone was placed in a vertical orientation giving the tunnel a "U" shaped layout as shown in Figure 11.

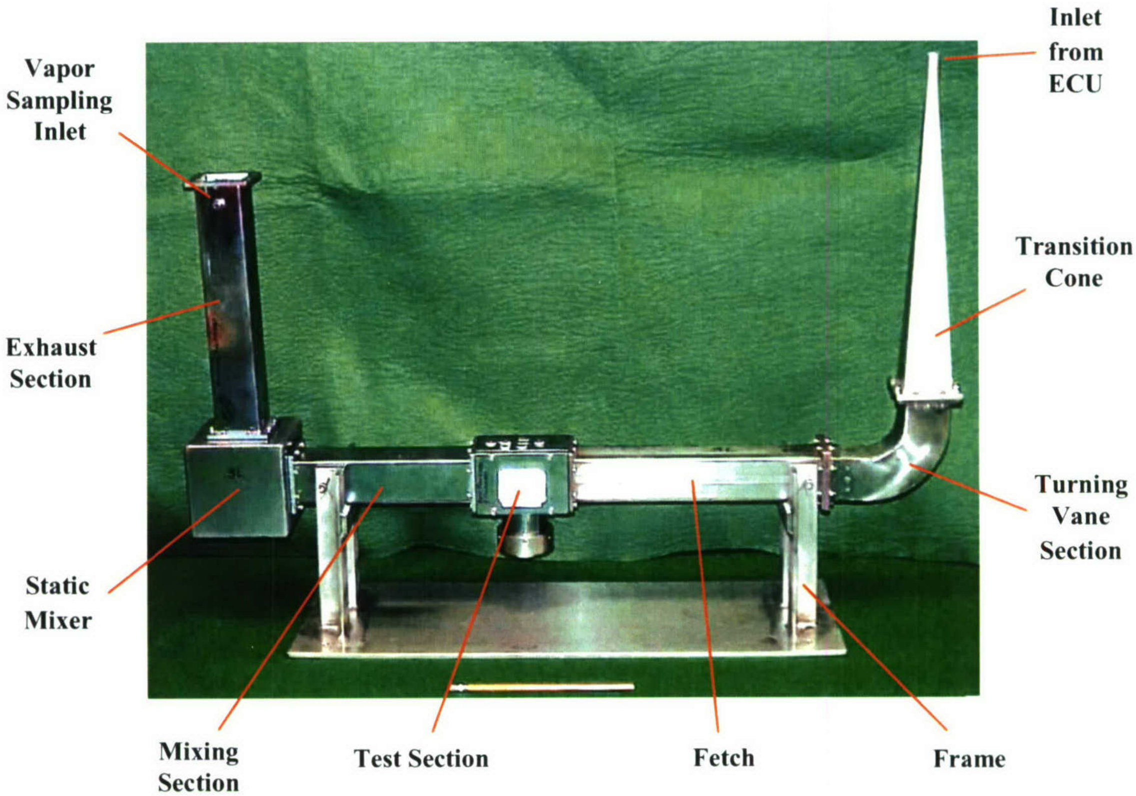


Figure 11. Version 3 Mod 1 Wind Tunnel

The horizontal orientation of the turning vane section of the Version 3 tunnel configuration resulted in any flow disturbances due to the vanes to act in a horizontal plane. While this influenced the variance of the profiles in a lateral sense, it had little effect on the more critical shape of the vertical velocity profiles. However, the vertical orientation of the turning vane section of the Version 3 Mod 1 tunnel configuration resulted in any flow disturbances due to the vanes to act in a vertical plane and consequently had a greater influence on the shape of the vertical velocity profiles. Based on velocity profile measurements, it was determined that the Version 3, Mod 1 tunnel required an inlet screen to eliminate air flow perturbations produced by the turning vanes. A 24 x 24 mesh per inch, 0.014 in. diameter wire screen was located at the exit of the turning vane section (the entrance of the fetch) as shown in Figure 12.

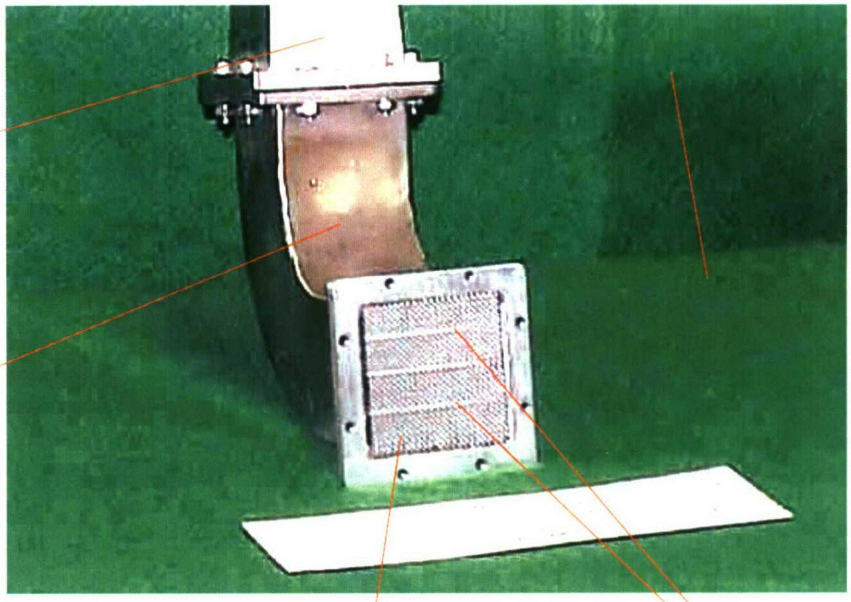


Figure 12. Fine Mesh for Vertical Oriented Turning Vane Section

Another modification incorporated into the Version 3 Mod 1 tunnel involved replacing the screw-in piston with a snap-in piston. This improved design allowed a more rapid insertion and removal from the tunnel than the previous screw-in piston design. This greatly reduced the time for the temperature to recover and for the start of the measurement of evaporation data during the crucial early portion of the test.

In preparation for tests with VX, a low volatility agent, all Version 3 Mod 1 tunnels were electro-polished and SulfInert® coated. The SulfInert® treatment provided an order of magnitude increase in resistance to absorption of VX vapor compared with the Silco-Steel® process. The Version 3 Mod 1 tunnel is being used for the major portion of the Agent Fate production testing.

A total of six Version 3 Wind Tunnels were originally fabricated (designated 3A through 3F) and three of these were used for the 5-cm Wind Tunnel validation tests with HD on glass and HD on sand. A total of six Version 3 Mod 1 tunnels were fabricated and designated 3G through 3L. Table 1 summarizes the current disposition of the twelve 5-cm Wind Tunnels and the status of their velocity characterization. The term "Complete" in the Velocity Characterization column means that vertical velocity profiles were measured for all three wind speeds at all five horizontal locations relative to the center of the substrate piston (i.e., center, upstream, downstream, left and right). The term "Abbreviated" means that a subset of velocities and positions were characterized. In the future, Version 3 Wind Tunnels may be upgraded to Version 3 Mod 1 Tunnels.

Table 1. Disposition and Use of 5-cm Wind Tunnels

Tunnel	Configuration	Name	Current Coating	Location	Velocity Characterization* Silco-Steel	Velocity Characterization* SulfInert	Employment
3A	3	Spartan	Silco-Steel	ECBC (E3300/227)	Abbreviated	-	High/Med Temp - Validation Tests: HD on Glass; Production Tests: HD/Sand
3B	3	-	SulfInert	ECBC (Aero Lab)	Complete	To Do	Ready to Assemble
3C	3	Grizzly	Silco-Steel	ECBC (E3300/227)	Abbreviated	-	High/Med Temp - Validation Tests: HD on Glass; Production Tests: HD/Sand
3D	3	Penguin	Silco-Steel	ECBC (E3300/227)	Abbreviated	-	Low Temp - Validation Tests: HD on Glass; Production Tests: HD/Sand
3E	3	-	SulfInert	Aero Lab	Abbreviated	To Do	
3F	3	Bearcat	SulfInert	Aero Lab	Complete	To Do	
3G	3 Mod 1	-	SulfInert	CUBRC		Abbreviated	GD on Teflon/Sand
3H	3 Mod 1	-	SulfInert	ECBC (Aero Lab)			
3I	3 Mod 1	-	SulfInert	ECBC		Abbreviated	
3J	3 Mod 1	-	SulfInert	ECBC (E3300/124)		Abbreviated	
3K	3 Mod 1	Nittany Lion	SulfInert	ECBC (E3300/124)		Abbreviated	VX
3L	3 Mod 1	Golden Gopher	SulfInert	ECBC (E3300/124)		Complete	VX

* Note: Tunnels 3B, 3E, and 3F were originally built and characterized as version 3 configurations and later converted to SulfInert Version 3, Mod 1 configurations and recharacterized.

4. VELOCITY PROFILES

4.1 Specified Operational Velocity Profiles

The approach adopted by the Agent Fate program was to define a set of nominal vertical velocity profiles, based on boundary layer theory and the "operational" wind conditions of interest to the Agent Fate model developers.[6] While somewhat arbitrary for simplified conditions, these profiles represent a practical bridge between the variable turbulent, unsteady, and omni-directional air flow in nature and the turbulent, steady, and parallel flow of the wind tunnel.

These velocity profiles were developed using boundary layer theory and are based on three values of Friction Velocities. Friction Velocity relates the shear stress produced by a boundary layer on the surface of the ground and is defined in Figure 13.

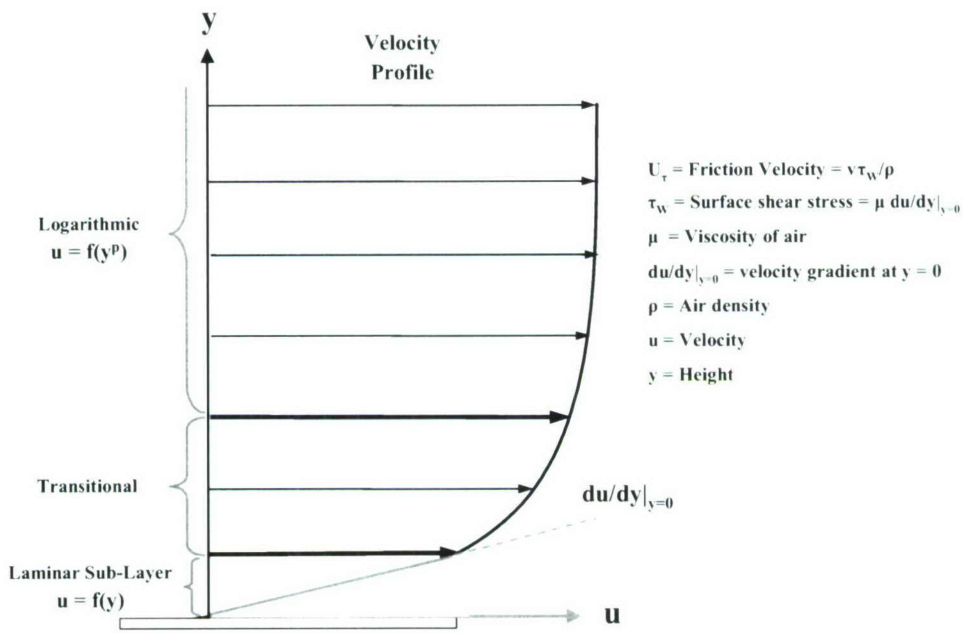


Figure 13. Velocity Profile Terminology

A set of three "operational" boundary layer velocity profiles were defined by the model developers as standard conditions for the wind tunnel studies. Figure 14 contains the original graph provided by the model developers and defines the near surface velocity profiles of an atmospheric boundary layer on a flat surface with some degree of roughness for wind speeds of 0.5, 3.0, and 6.0 m/s at a 2 m height above the ground. Wind velocity conditions at 2 m were selected based on operational conditions intended to be included in the final Agent Fate models. The Friction Velocities selected for the Agent Fate experiments correspond to relatively smooth surfaces (glass, metal, sand, soil, concrete and asphalt). The choice of these friction velocities defined their respective velocity profiles.

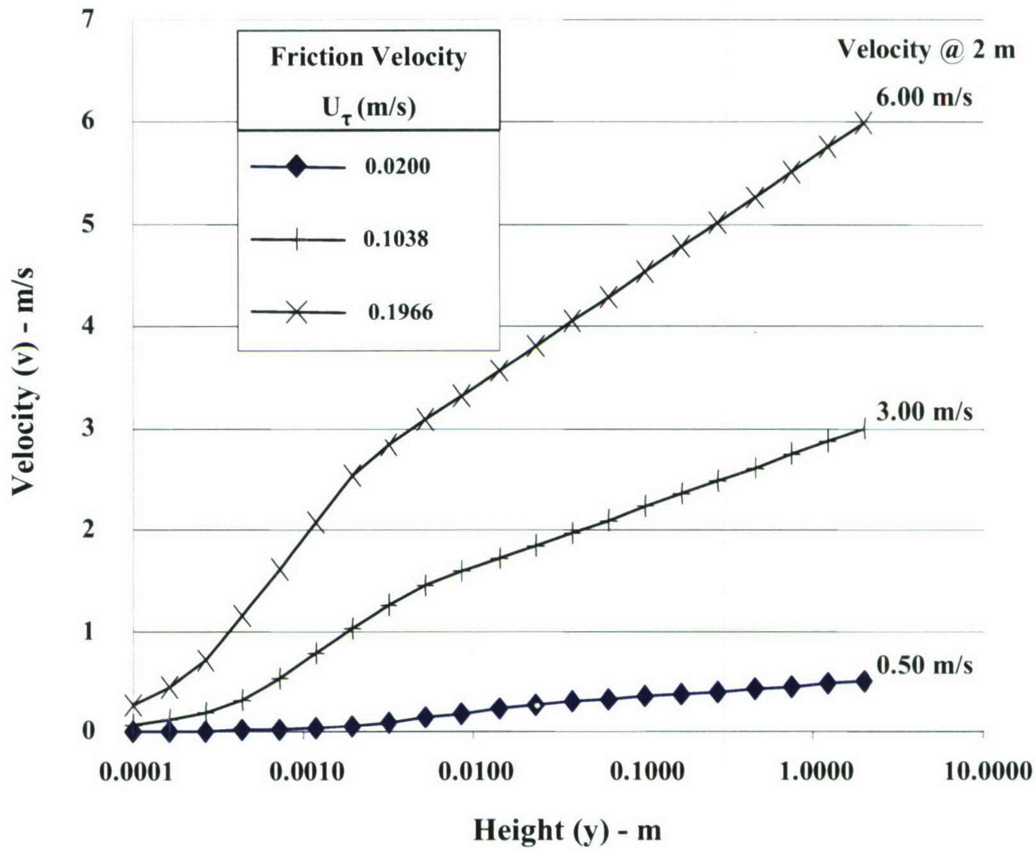


Figure 14. Operational Velocity Profiles

Figure 15 shows the three operational velocity profiles in non-logarithm units and provides a better physical "feel" for the shape of the velocity profile. While the operational velocity profile is defined for a wind velocity at a height of 2 m, the 5-cm Wind Tunnel only needs to duplicate the velocity profile up to a height of 2 cm as shown in Figure 16. The velocities at a height of 2 cm in the 5-cm Wind Tunnel of 0.22, 1.7 and 3.6 m/s correspond to the 0.5, 3.0 and 6.0 m/s test matrix velocities, respectively. Hot wire anemometer measurements in the 5-cm Wind Tunnel test section had demonstrated that the stipulated operational vertical velocity profiles were created at these reference velocities. Thus, setting the 2-cm reference velocity at a specific test matrix value was sufficient to establish the associated operational vertical velocity profile. The reference height was later lowered to 1 cm for the production tests.

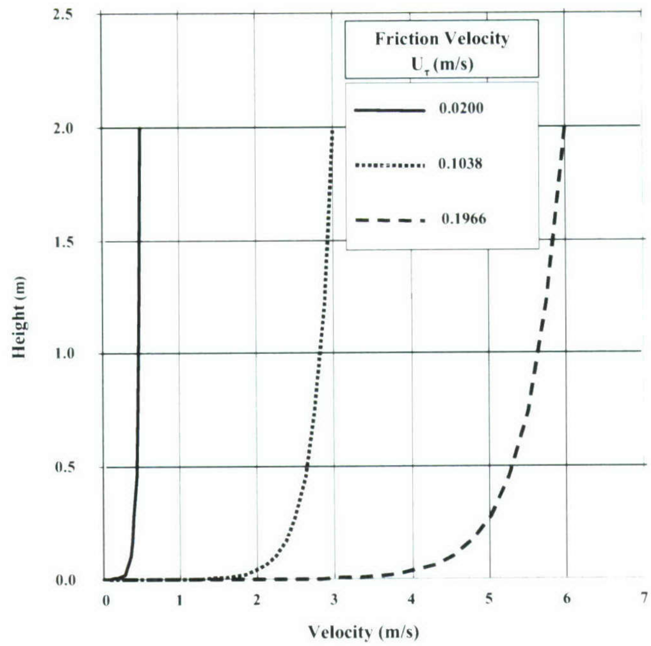


Figure 15. Operational Velocity Profiles in Physical Units

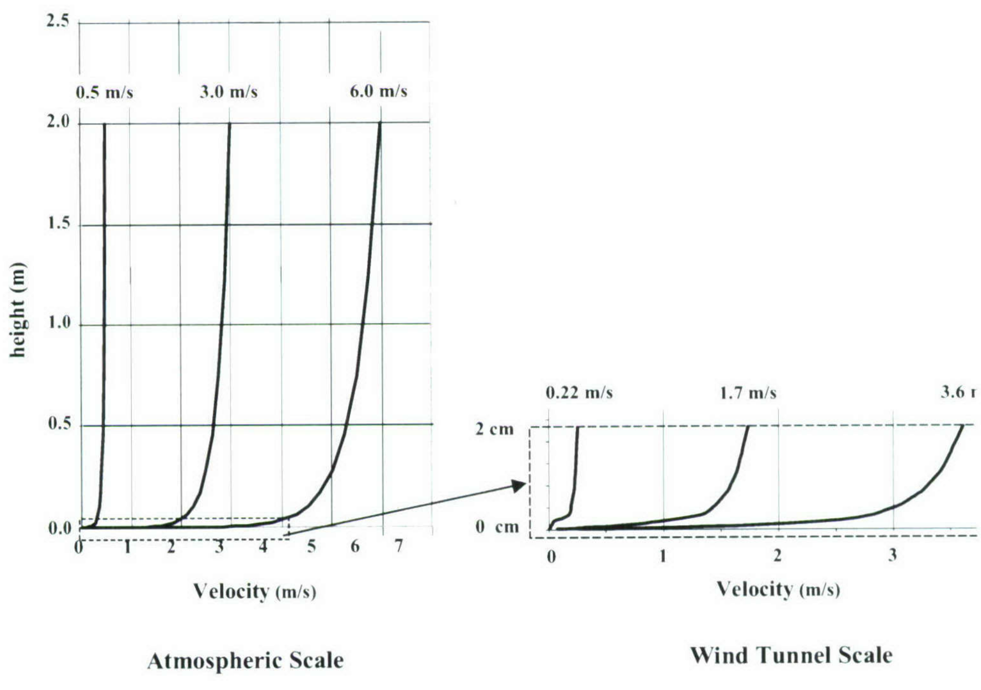


Figure 16. Lower Portion of Operational Boundary Layer Profiles

The enlarged plot of the profiles contained in Figure 16 shows the characteristic (and unrealistic) "dog leg" shape of the low operational velocity profile in the vicinity of the floor. This is due to the manner in which the transition between the laminar sub-layer and the exponential portions of the theoretical profile was established when the profiles were defined. The measured (and realistic) shape exhibits a smoother curve. A possible explanation for this unrealistic shape may be due to the application of turbulent boundary layer equations to the low velocity case, where turbulent flow is not possible.

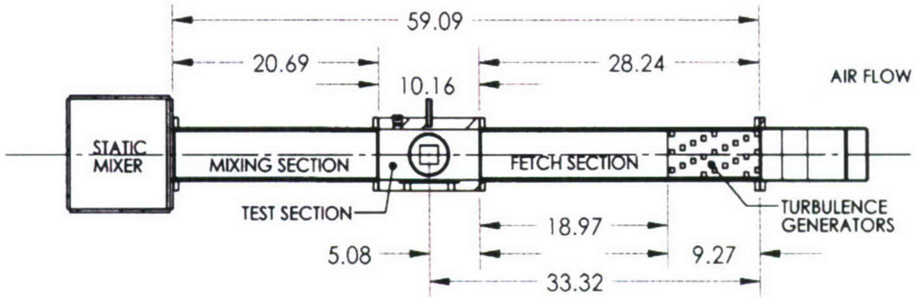
4.2 Formulation of 5-cm Wind Tunnel Velocity Profiles

The 5-cm Wind Tunnel utilizes a series of turbulence generators located upstream of the test section to produce the specified operational vertical velocity profiles over the agent/substrate. These turbulence generators consisted of an array of cubical blocks placed along the floor at the beginning of the fetch. The turbulence created by these blocks produce vertical velocity profiles that closely match the three operational profiles. The location of the turbulence generators relative to the test section is described in Figure 17 and details of the turbulence generator array are shown in Figure 18.

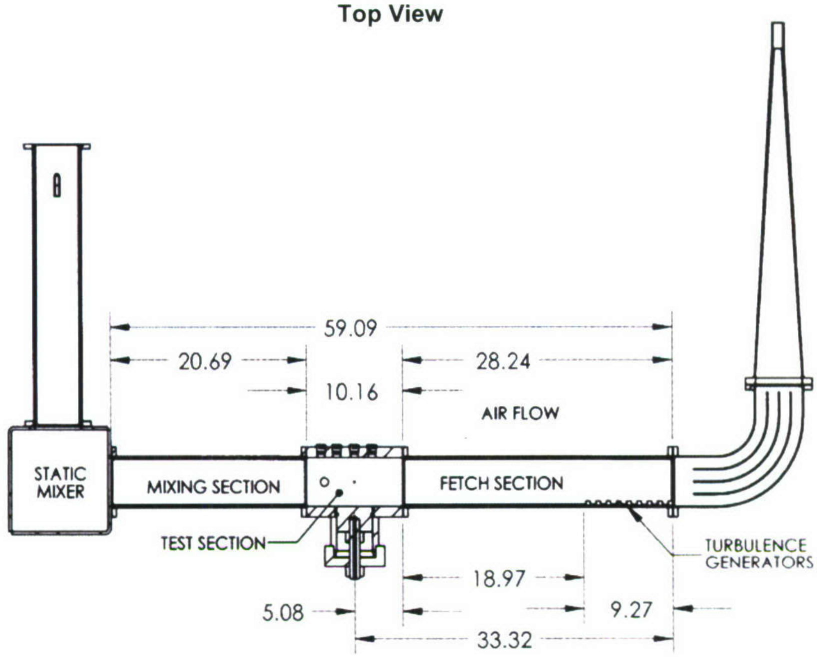
5. 5-CM WIND TUNNEL VELOCITY CHARACTERIZATION

5.1 Overview of Velocity Characterization

"Characterization" refers to the detailed measurement of the vertical velocity profiles in the test section of the 5-cm Wind Tunnel and relating these profiles to a reference velocity that could be easily measured in the tunnel during routine production tests. The characterization process was complicated by the small size of the test section, the relatively low velocities and the large range of temperature and relative humidity conditions, and the limited number of access ports. Selection of the velocity measurement instrumentation and its subsequent use was a critical element.

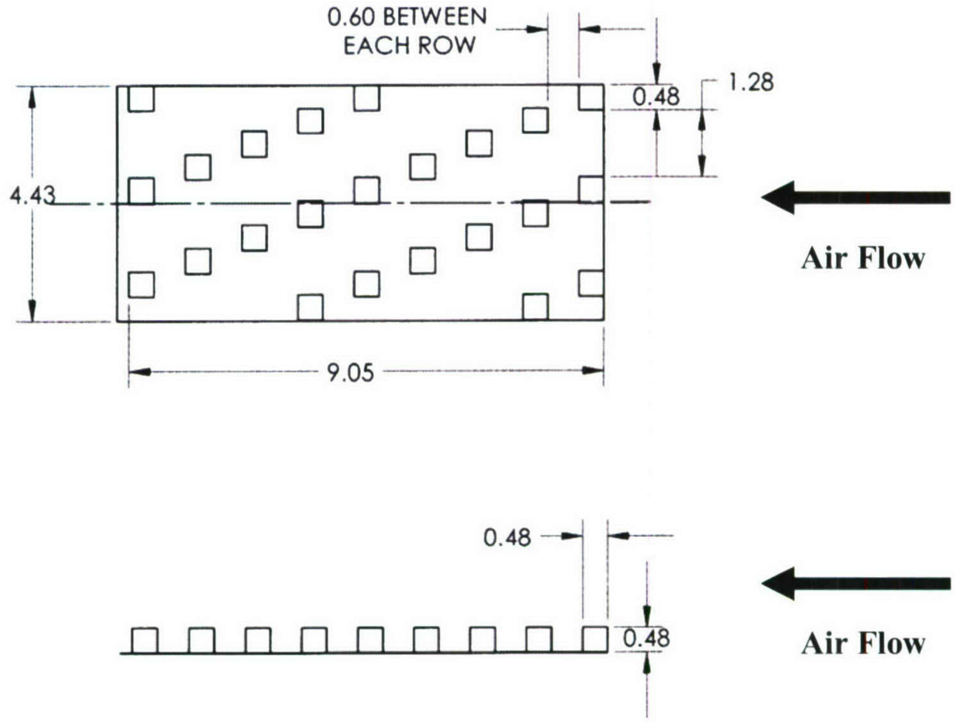


Top View



Front View

Figure 17. Location of Turbulence Generators Relative to Test Section (dimensions in cm)



Front View

Figure 18. Details of Turbulence Generator Array
(dimensions in cm)

5.2 Characterization Instrumentation

5.2.1 Hot Wire Anemometers

5.2.1.1 Overview Hot Wire Anemometry

Several techniques were considered to measure the velocity profiles including pitot-static tubes, Particle Imaging Velocimeter (PIV), Laser Doppler Anemometry (LDA) and hot wire anemometry. Each had advantages and disadvantages, but hot wire anemometry provided the best approach for meeting the velocity profile measurements required for the 5-cm Wind Tunnel.

A Constant Temperature Anemometer (CTA) operates by having a current passed through a small wire and heating it to 200-300 °C. When air flows over the wire, heat is lost by convection and the wire cools. The anemometer contains an electronic feedback circuit that increases the current/voltage to maintain a constant hot wire temperature. The velocity of the air flow over the wire is proportional to the voltage change required to maintain the wire

temperature. Calibration curves are generated relating air speed to circuit voltage for constant air temperatures. A major difficulty in hot wire anemometry is faced when measuring wind speed in air that is at a different temperature from existing calibration curves. Because the CTA works on heat transfer, errors in velocity readings can occur for air temperatures not accounted for by either previous calibration, electronic adjustment of the hot wire overheat ratio, or analytical corrections to the hot wire output voltage. Corrections for air temperature differences depend on the type of hot wire anemometer employed. Industrial type hot wire anemometers intended for Heating, Ventilation, and Air Conditioning (HVAC) work typically well for air temperature electronically using a temperature sensor placed near the hot wire sensor. Research grade systems usually rely on a combination of multiple calibration curves at different air temperatures and/or analytical techniques.

Both types of hot wire anemometers were used with the 5-cm Wind Tunnel. The detailed characterization was performed with a research grade anemometer and an industry HVAC grade anemometer was used to measure the reference velocity during the actual testing in the tunnel.

5.2.1.2 Characterization Hot Wire Anemometer

Characterization measurements were performed using a TSI Miniature Straight Hot Wire Probe (Model 1260A).[7] This probe was calibrated for wind speeds as low as 0.05 m/s. A high speed analog to digital converter was utilized along with a dedicated software program. In addition to velocity, the device also measures turbulence intensity, Reynolds stress and other statistical quantities. Multi-component hot wires are available which allow velocities to be measured in two and three components, these are larger, more complicated to calibrate and use and do not offer as fine a spatial resolution as a single component probe. Accordingly, all of the 5-cm characterization measurements were done with a single-component hot wire. This was also felt to be sufficient in that the air flow in the 5-cm Wind Tunnel test section is essentially uni-directional. Figure 19 contains a photograph of the basic TSI Model 1260. A hot film probe with its dimensions is shown in Figure 20.

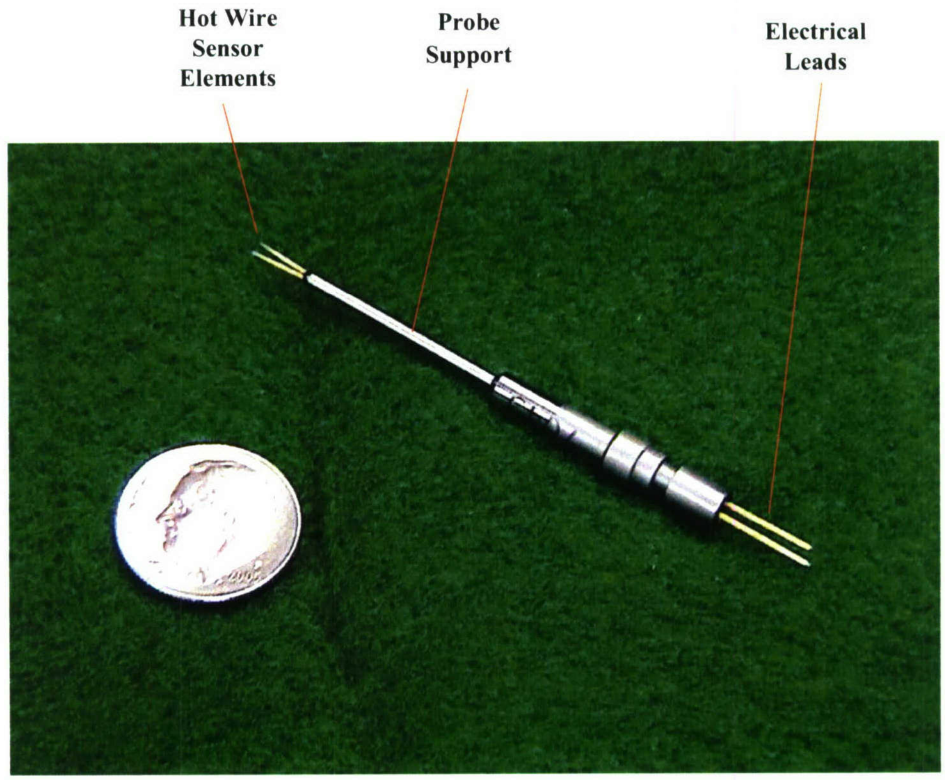


Figure 19. TSI Miniature Straight Hot Wire Probe (Model 1260A)

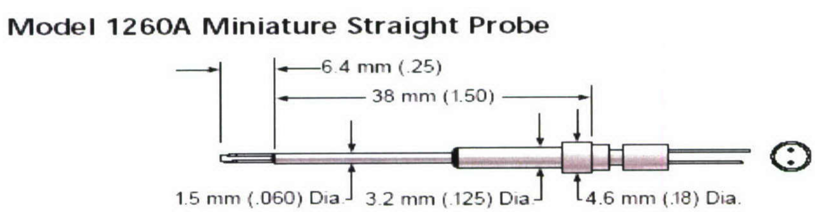


Figure 20. Dimensions of TSI Hot Wire Probe (Model 1260A)

The Model 1260A hot wire anemometer operates in conjunction with the TSI IFA 300 controller shown in Figure 21. When air flows over the wire, heat is lost by convection and the wire cools. The anemometer contains an electronic feedback circuit that increases the current/voltage to maintain a constant hot wire temperature. Through the electronics of the IFA300, the temperature of the sensor is held constant by increasing the current through the sensor which is outputted from the IFA300 as a voltage difference. This voltage is supplied to an analog to digital converter inside a computer. The velocity of the air flow over the wire is proportional to the voltage change required to maintain the wire temperature. Specialized software (ThermalPro®) developed by TSI provides complete control of the IFA300 from calibration through the actual measurement process, to velocity data analysis. An important feature of the IFA300 is its ability to measure high frequency velocity fluctuations, which is contributes greatly to the study of turbulent flow fields. The system also incorporates a thermocouple for measuring air temperature for applying off-calibration temperature corrections.

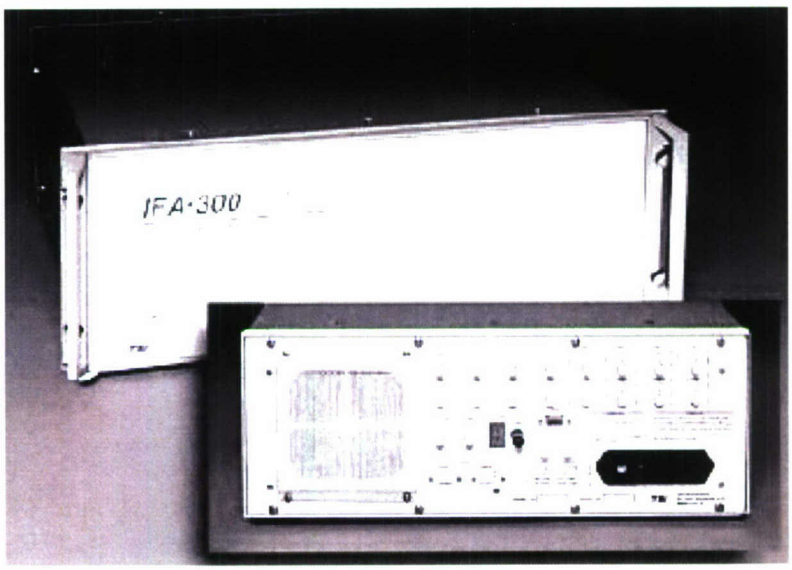


Figure 21. TSI IFA 300 Thermal Anemometry Systems

It is generally recommended that the probe be installed so that the flow is parallel to the needle like hot wire supports. However, due to the reasons just cited, straight probes were used in characterizations of the ECBC tunnel with the wire supports oriented perpendicular to the flow. This is an acceptable procedure for probes calibrated perpendicular to the wind direction as is the case with the 5-cm Wind Tunnel.

5.2.1.3 Hot Wire Anemometer Calibration

A research grade hot wire anemometer requires accurate calibration for the range of air flow temperatures for which it is being used. This calibration was performed using a TSI Model 8390 bench top wind tunnel illustrated in Figure 22. The calibration wind tunnel incorporates a 10-cm^2 cross-section test section which can be configured by adding or removing supplied orifice plates to cover a manufacturer specified wind speed range of 0.15 to 45.7 m/s. The tunnel air flow is provided by a fan located downstream of the test section powered by a variable speed, electric motor. The test section velocity had been previously measured by TSI using a laser doppler velocimeter and these measurements are correlated to the static pressure difference between the settling chamber and test section. To accommodate the expected low wind speeds near the floor of the 5-cm Wind Tunnel, the lower calibration wind speed value was lowered to 0.05m/s, which was near the lower limit of the lab's pressure measuring capabilities. The anemometer being calibrated was inserted through the side of the calibration wind tunnel's test section so that the tip of the anemometer was located at the center of the test section.

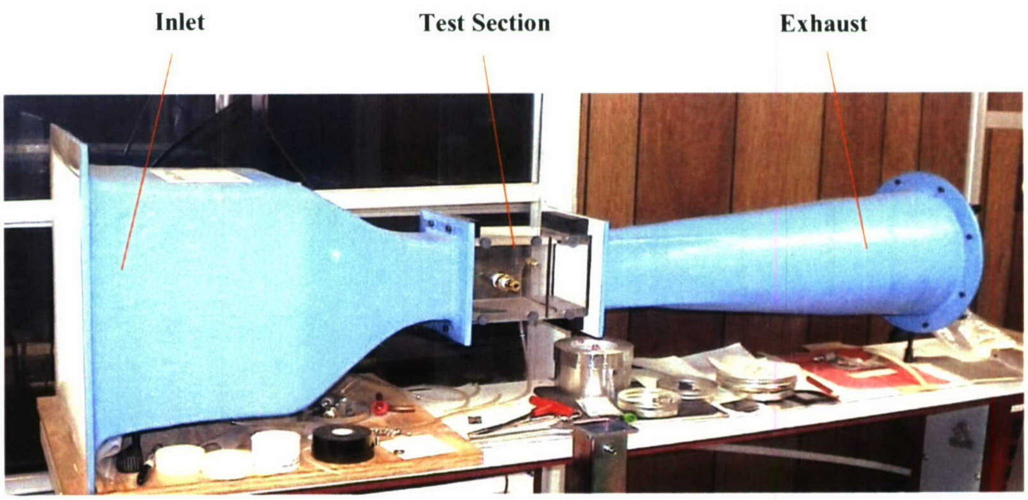


Figure 22. TSI Model 8390 Hot Wire Anemometer Calibration Wind Tunnel

The detailed procedure followed in calibrating the TSI Model 1260A anemometer is described in Appendix I.

5.2.1.4 Reference Velocity Hot Wire Anemometer

The velocity characterization was performed using a research grade anemometer. This demonstrated that the wind tunnel being tested produced the required test matrix velocity profiles. During the actual wind tunnel tests of agents/substrates, the desired velocity profiles were established by setting the tunnel air flow through the measurement of a reference velocity at a specific height from the test section floor. This reference velocity was correlated to the particular test matrix velocity profile being considered. A TSI Air Velocity Transducer Model 8465 hot wire anemometer[8] was employed to measure the reference velocity during testing operations. A picture of the Model 8455 is shown in Figure 23.

Figure 23. TSI Air Velocity Transducer Model 8465

This device, while not as sensitive and accurate as a research level anemometer, was more robust and less prone to damage or changes in calibration during the long, sustained production testing operations with the 5-cm Wind Tunnel. It was also thinner and was less obtrusive to the air flow in the passing over the drop/substrate than the research grade device. The Model 8465 hot wire sensor is a thin needle like wire that protrudes from the end probe tip. The hot wire sensor is not protected thus reducing flow blockage which might otherwise adversely affect the wind speed measurement in confined spaces. A close-up of tip is shown in Figure 24.

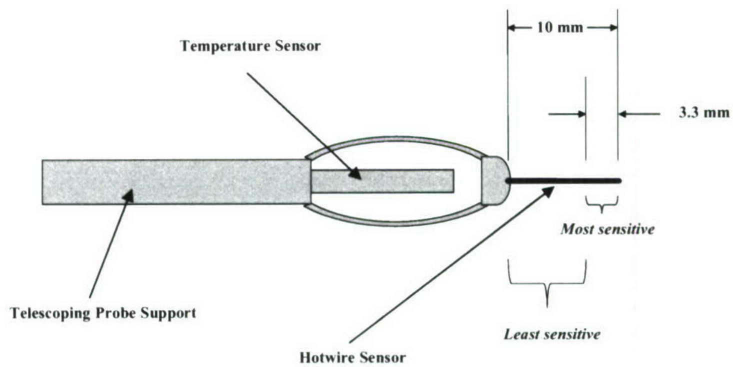


Figure 24. Schematic of Model 8465 Hot Wire Probe

The Model 8465 is a relatively low cost, active temperature compensated device. The small probe size allows very accurate placement of the probe tip with respect to the tunnel floor, while also incorporating some degree of ruggedness that research type hot wire sensors do not. The sensor overheat ratio for the Model 8465 is typically lower than those used by research hot wire systems thus reducing the chance of convection affecting the velocity readings near a surface. The operational fluid temperature range of this device is 0 to 60 °C, with an accuracy of ±2% of the reading. However, this accuracy is only valid over a temperature range of 18 to 28 °C. Outside of this range (0 to 18 °C and 28 to 60 °C) an additional 0.2% per °C must be added to the ±2%. Thus if the air temperature was 50 °C, the accuracy would be ±6.4%.

This anemometer is intended to make average flow measurements in the center of relatively large ducts and is not suited for boundary-layer measurements. This probe works best when the entire tip is immersed in the flow field where the velocity is nearly constant. In a non-uniform flow field such as within a boundary-layer, the probe would measure an average velocity over the length of the 10 mm probe length. However, it is adequate for reference velocity monitoring in the vicinity of the centerline of the 5-cm Wind Tunnel where the vertical velocity profile is relatively constant.

The tunnel air flow rate was established by measuring the velocity in the test section at a reference height above the test section floor using a hot wire anemometer and adjusting the wind tunnel flow controller to achieve the test matrix reference velocity desired. Based on the velocity characterization, this provided the stipulated velocity profile in the test section as shown in Figure 25. The velocity values at a 2-cm height are the source of the 0.22, 1.7, and 3.6 m/s for the low, medium and high operational velocities, respectively.

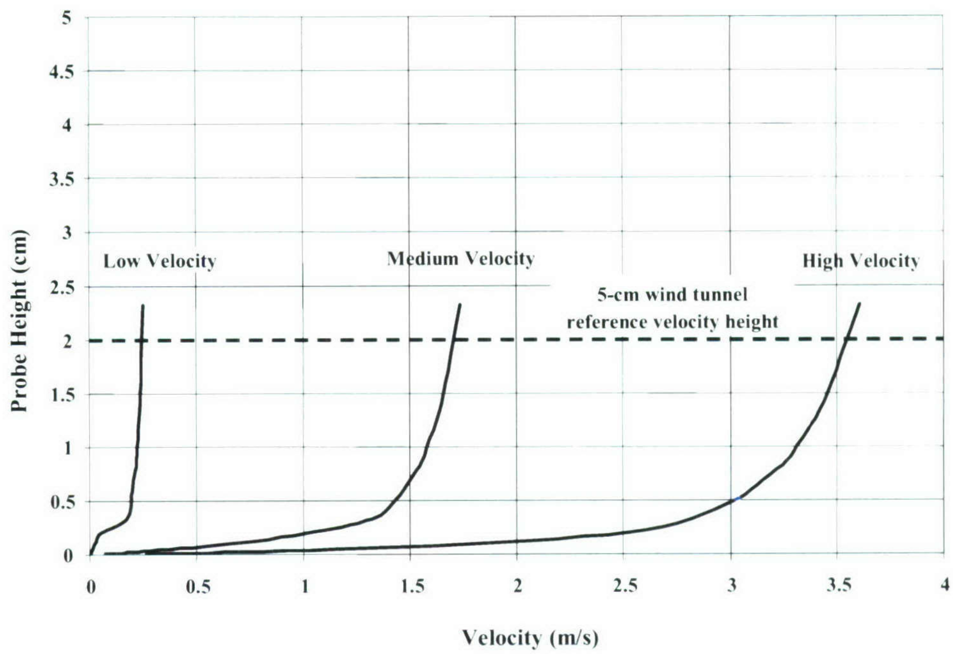


Figure 25. 5-cm Wind Tunnel Reference Velocities

5.3 Characterization Arrangement and Process

The characterization process required a positioning device to accurately place the hot wire probe at specific heights above floor of the test section. A 24 in. commercially available height gage (24 in. Mitutoyo Series 192) was modified to position the probe holder through the instrumentation ports in the test section ceiling. This permitted precise vertical positioning of the hot wire sensor relative to the tunnel floor. Figure 26 shows the hot wire anemometer positioning system with the 5-cm Wind Tunnel. A rubber balloon was used as a flexible seal to prevent air leakage through the port hole in the test section ceiling and the hot wire support strut. A close-up photo of the anemometer probe in the tests section is contained in Figure 27.

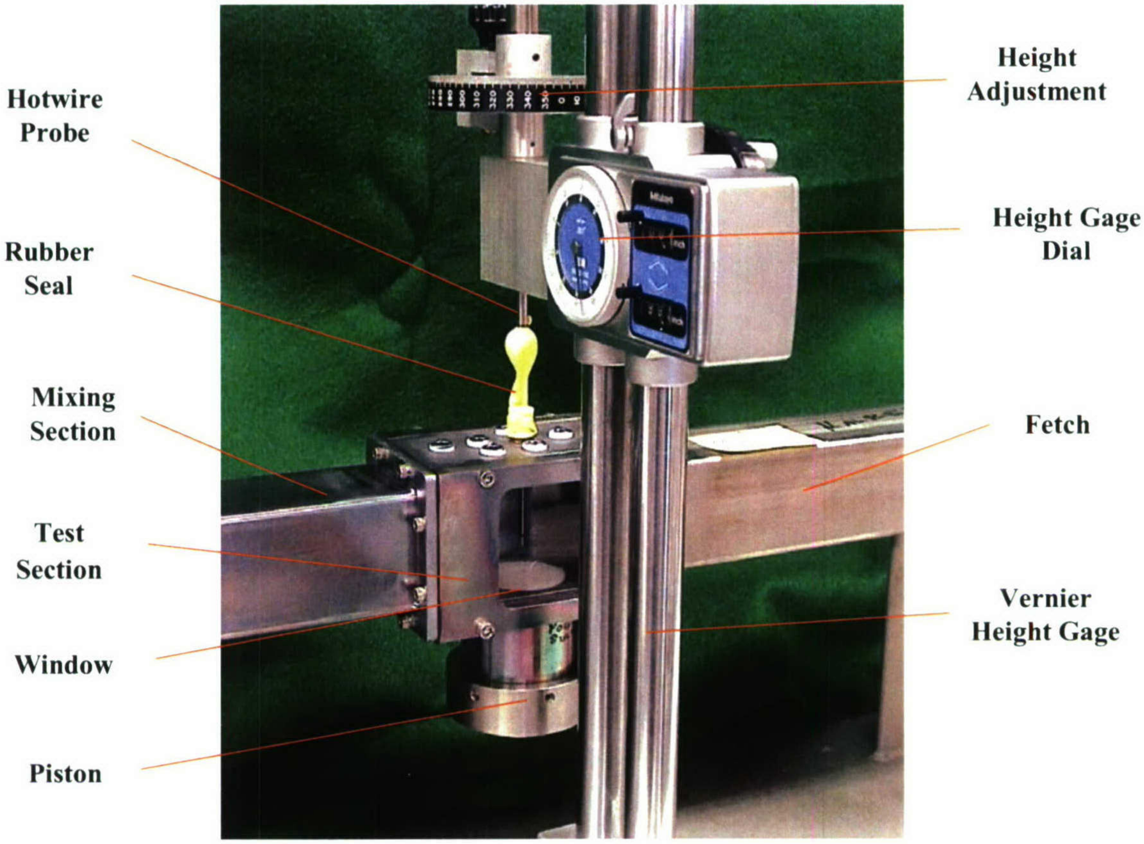


Figure 26. Hot Wire Vertical Positioning Apparatus

Figure 27. Hot Wire Probe in Test Section

A complete characterization consisted of measurements of the vertical profiles at all five horizontal locations relative to the center position defined as the center of the substrate piston (i.e., center, upstream, downstream, left and right). The details of the test section and measurement positions are shown in Figures 28, 29, and 30.

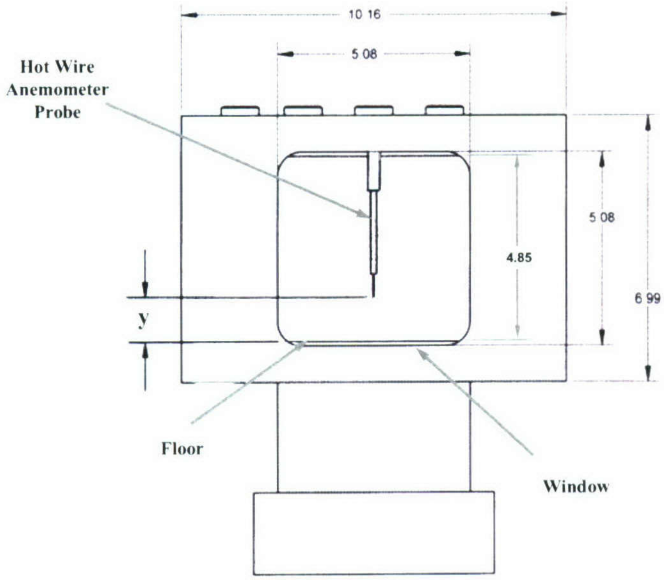


Figure 28. Side View of 5-cm Wind Tunnel Test Section Showing Hot Wire Anemometer Probe Height (y) for Velocity Profile Characterization

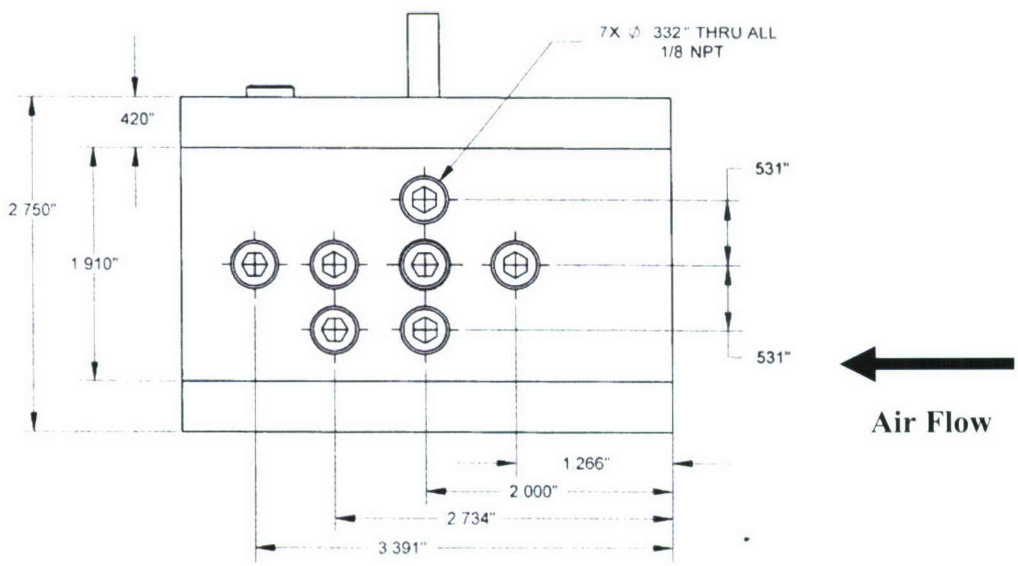


Figure 29. Top View of 5-cm Wind Tunnel Test Section Showing Hot Wire Anemometer Probe Locations Used for Velocity Profile Characterization

Position	Location	Distance from Center inches	centimeters	% test section width	% test section length
A	Center	0.0	0.0	0.0	0.0
B	Left	0.531	1.349	27.500	13.275
C	Right	0.531	1.349	27.500	13.275
D	Upstream	0.734	1.864	38.400	18.350
E	Downstream	0.734	1.864	38.400	18.350

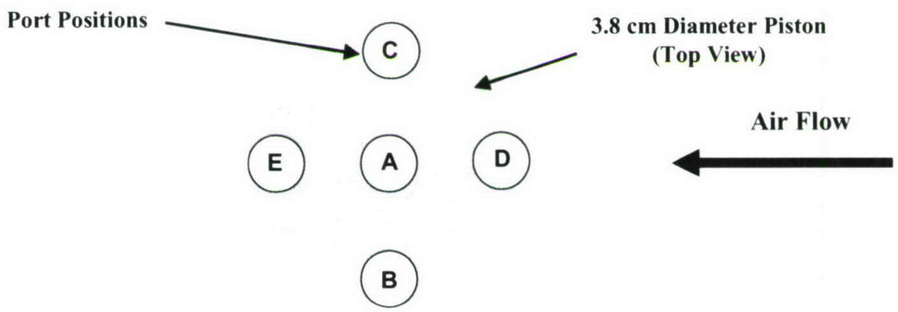


Figure 30. Positions for Vertical Velocity Profile Measurements

A typical characterization consisted of 21 velocity and turbulence intensity measurements starting from a location 0.05 in. (1.25 mm) above the test section floor and proceeding in increments of 0.05 in. (1.25 cm) to a height of 0.295 in. (7.5 mm). From this height onwards, the increment was changed to 0.10 in. (2.5 mm) and the process continued to a height of 1.77 in. (45 mm). A detailed description of the characterization procedure is contained in Appendix II.

Figure 31 contains representative velocity measurements in the 5-cm Wind Tunnel at the center position (A) compared to the corresponding stipulated operational values. Data are shown in both logarithmic and physical units. It should be remembered that the critical region of the profile is nearest the floor of the test section in the vicinity of the agent and substrate. Note the good agreement between measured and operational values.

5.4 5-cm Wind Tunnel Velocity Profiles

5.4.1. Overview of Velocity Profiles

As noted previously, a design goal for the 5-cm Wind Tunnel was to allow it to be replicated in large numbers (10-20) and used in multiple locations. Even though each tunnel had identical dimensions, it was important to demonstrate that each of the tunnels recreated the desired vertical velocity profiles. Table 2 summarizes the extent of characterization for the initial twelve 5-cm Wind Tunnels.

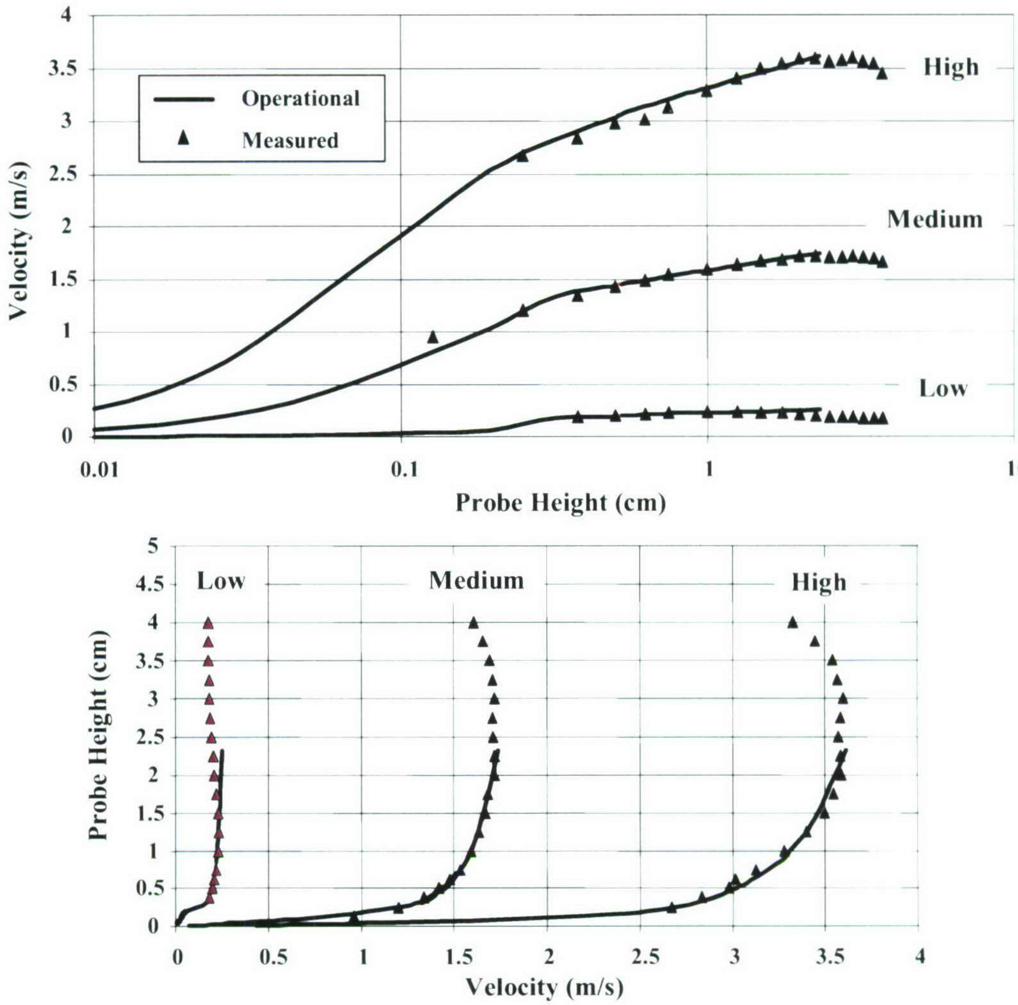


Figure 31. Velocity Profiles Measured at the Center (Position A) of the 5-cm Wind Tunnel in Both Physical and Log Scales (Tunnel 3B)

Table 2. Summary of 5-cm Wind Tunnel Velocity Profile Characterizations

Tunnel	Configuration	Velocity	Position A	B	C	D	E
3A	3	Low	x				
		Medium	x				
		High					
3B	3	Low	x	x	x	x	x
		Medium	x	x	x	x	x
		High	x	x	x	x	x
3C	3	Low	x				
		Medium	x				
		High	x				
3D	3	Low	x				
		Medium	x				
		High	x				
3E	3	Low	x				
		Medium	x				
		High	x				
3F	3	Low	x	x	x	x	x
		Medium	x	x	x	x	x
		High	x	x	x	x	x
3G	3 Mod 1	Low	x				
		Medium	x				
		High	x				
3H	3 Mod 1	Low					
		Medium					
		High					
3I	3 Mod 1	Low	x				
		Medium	x				
		High	x				
3J	3 Mod 1	Low	x				
		Medium	x				
		High	x				
3K	3 Mod 1	Low					
		Medium	x				
		High					
3L	3 Mod 1	Low	x	x	x	x	x
		Medium	x	x	x	x	x
		High	x	x	x	x	x

The original goal was to characterize the velocity profiles (i.e., measure the velocity profiles for all three test conditions) at the center test section position for all tunnels and perform a complete characterization (at all five test section positions - center and upstream, downstream, left, and right of the center) for at least one each of the Version 3 and Version 3 Mod 1 tunnels. Two repetitions were performed for each test condition. At the time of this report, complete characterizations have been completed for tunnels 3B, 3F an 3L. Tunnel 3D through 3F are expected to eventually be converted to the Version 3 Mod 1 configuration and will be re-characterized at the center location only. Tunnel 3H has not been characterized as yet.

The following section contains the plotted vertical velocity profiles for all of the 5-cm Wind Tunnels along with the corresponding operational profiles. Profiles are shown for the positions (Position A through E) and velocities tested in each wind tunnel for the nominal 35 °C temperature. The results of additional tests to evaluate the effect of temperature, surface roughness and turbulence screens are also discussed. While vertical velocities were measured

across the entire height of the test section, only the portion of the profile near the floor is of importance since this is the region that affects the sorption and evaporation rates of the agent/substrate that are the main items of interest in the Agent Fate Program. Accordingly, the turbulence generators were intended to only influence the bottom portion of the velocity profile (i.e., between 2 cm and the floor of the test section).

Table 3 shows the difference between the measured and operational velocity values at a height of 1 and 2 cm above the test section floor for all of tunnels and conditions tested in the 5-cm Wind Tunnel. The values shown are the average of the repeated runs. These numbers provide an indication of the ability of the 5-cm Wind Tunnel to match the desired velocity conditions and associated velocity profiles.

At 2 cm, the velocity values at the center of the piston (position A) were within about 3% with a standard deviation of about 12% of the operational value for all of the tunnels. All positions had slightly higher velocities than the operational value ranging from 3 to 12%. The lateral positions (B and C) had differences of 12 and 5%, respectively, with about the same 5% deviation with the position closest to the window having the higher values. The upstream and downstream positions (D and E) had average differences of about 4% with the upstream position having the largest deviation value of 9%.

The values at 1-cm height were even better. The velocities at the center of the piston (position A) were within about 1% with a standard deviation of about 4% of the operational value for all of the tunnels. The lateral positions (B and C) were similar and exhibited slightly lower velocities ranging from 2 to 6% with standard deviations of about 4%. The upstream and downstream positions (D and E) had average differences of about 4 and 1%, respectively, with the upstream position having the largest deviation value of 16%.

A closer examination reveals that the largest average values and standard deviations are those at the 2-cm height for the low velocity condition. As will be discussed in Section 8, this represents a fully laminar profile and is a special situation as compared to the fully turbulent profiles of the medium and high velocities. For the latter two conditions, the average difference and standard deviation values at all positions and both heights never exceed 6%.

These observations indicate the general ability of the 5-cm Wind Tunnel to accurately and repeatedly achieve the reference velocities and associated velocity profiles stipulated by the Agent Fate test matrix. . A more rigorous quantitative analysis of the velocity profiles based on boundary layer theory is contained in Section 8 of this report.

Table 3. Percent Difference between Measured and Operational Velocities

Percent Difference Between Measured* and Operational Velocities in 5-cm Wind Tunnel

		1 cm Height					2 cm Height				
		Position					Position				
	Tunnel	A	B	C	D	E	A	B	C	D	E
Low Velocity	3A	0.7					-3.4				
	3B	0.5	3.4	0	10.9	5.2	-18.2	-1.4	-6.1	-14.5	-2.3
	3C	0.2					-15				
	3D	4.8					1.6				
	3E	5					-12.5				
	3F	-3.4	-10.5	1.1	45.5	3.9	-23.6	-12	-7.3	16.6	-17
	3G	6.6					12				
	3G Mod 1										
	3H Mod 1										
	3I Mod 1	-3.6					-29.7				
	3J Mod 1	12					-26.8				
	3K Mod 1	-3.6					-15				
	3L Mod 1	-1.8	-10	-1.8	-3.2	4.1	-14.4	-18.6	-15	-15	-13.6
Medium Velocity	3A	-1					2.5				
	3B	0.9	-4.8	-2.1	1.7	1.3	8	-13	-4.4	0.6	0.8
	3C	-2.3					3				
	3D	1.6					0.4				
	3E	1.6					4.5				
	3F	1.2	-7.8	3.2	-6.7	-4.1	7.3	-11.1	2	-5.4	-3.6
	3G	0					1.2				
	3G Mod 1	3					-1.4				
	3H Mod 1										
	3I Mod 1	3.3					1				
	3J Mod 1	6.7					-1.8				
	3K Mod 1	1.5					10.8				
	3L Mod 1	-0.6	-2.9	-7.6	-2.2	-0.3	-1.7	-5.8	-4.1	-3.2	-4.2
High Velocity	3A										
	3B	3.8	-12.8	-7.5	-4.9	-2.1	2	-24	-7.9	-6.1	-5.3
	3C	-0.7					2.1				
	3D	1.2					0.8				
	3E	0.1					3.1				
	3F	-1	-7.8	0.7	-3.8	-1.5	-0.2	-14.2	-0.6	-1	-0.5
	3G	-9.9					-1				
	3G Mod 1	0.4					0.6				
	3H Mod 1										
	3I Mod 1	2.8					1.8				
	3J Mod 1	6.7					3.6				
	3K Mod 1	0.8					2.5				
	3L Mod 1	0.5	-2.2	-5.9	-0.5	0.8	-0.9	-5.8	-4.8	-1.6	-3.2
	Average	1.1	-6.2	-2.2	4.1	0.8	-2.8	-11.8	-5.4	-3.3	-5.4
	Std Dev	3.8	5.0	3.9	16.4	3.1	10.3	6.9	4.8	9.3	6.0

* Note: Average of all runs

		1 cm Height					2 cm Height			
		Position					Position			
		A	B	C	D	E	A	B	C	D
Low Velocity	Average	1.6	-5.7	-0.2	17.7	4.4	-13.2	-10.7	-9.5	-4.3
	Std Dev	5	7.9	1.5	25.1	0.7	12.4	8.7	4.8	18.1
Medium Velocity	Average	1.3	-5.2	-2.2	-2.4	-1	2.8	-10	-2.2	-2.7
	Std Dev	2.3	2.5	5.4	4.2	2.8	4.1	3.7	3.6	3
High Velocity	Average	0.4	-7.6	-4.2	-3.1	-0.9	1.3	-14.7	-4.4	-2.9
	Std Dev	4.1	5.3	4.3	2.3	1.5	1.6	9.1	3.7	2.8

5.4.2 Tunnel Version 3

5.4.2.1 Tunnel 3A

Vertical velocity profiles for tunnel 3A were measured only at the low and medium velocities at the center position. Characterization was cut short to allow the tunnel to be installed in the fume hood, instrumentation incorporated and validation tests begun so that instrumentation, testing procedures and other issues could be identified. As can be seen in Figures 32, good agreement with the operational profiles was achieved with very good repeatability.

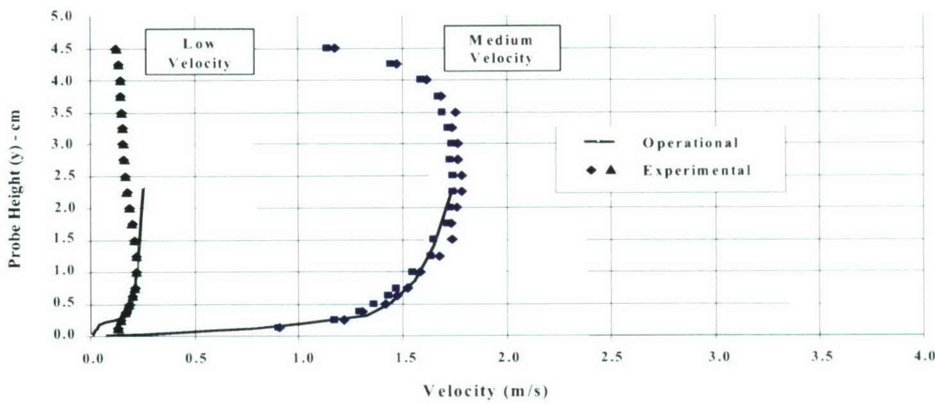


Figure 32. Measured Velocity Profiles for Tunnel 3A

5.4.2.2 Tunnel 3B

While tunnel 3A was being used to evaluate various instrumentation arrangements and validate the 5-cm tunnel design, a complete velocity characterization was performed on tunnel 3B.

Figure 33 shows the vertical velocity profiles measured at the center position (Position A) for all three velocities compared with their respective operational profiles at the center position.

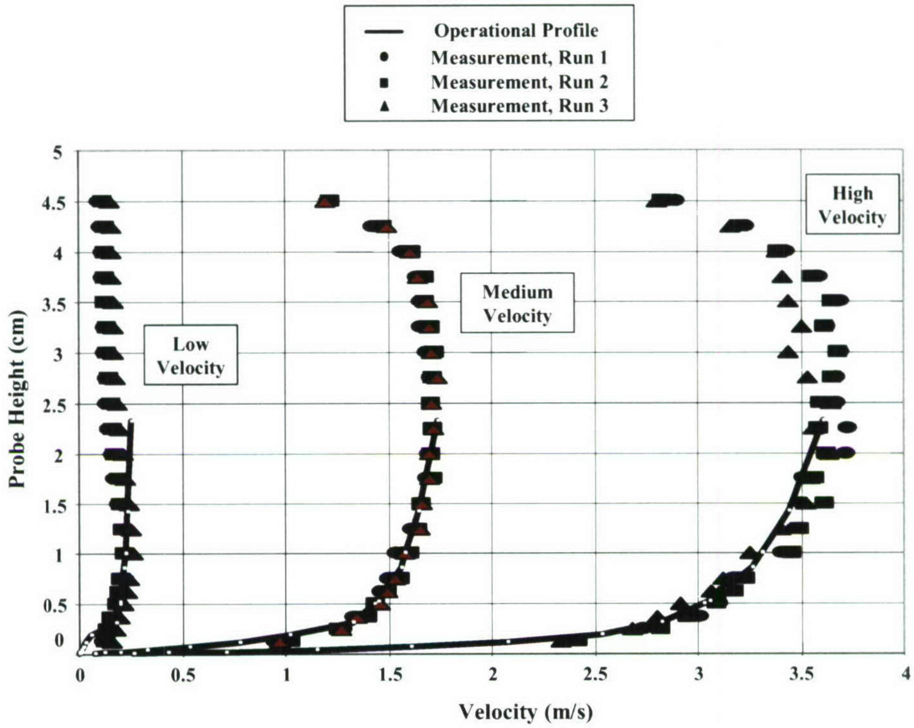


Figure 33. Measured Velocity Profiles for Tunnel 3B (Position A)

Figure 34 contains the vertical velocity profiles measured in tunnel 3B at all five positions for the low velocity compared with the operational profile. As can be seen, there is virtually no difference in the profile across the piston area.

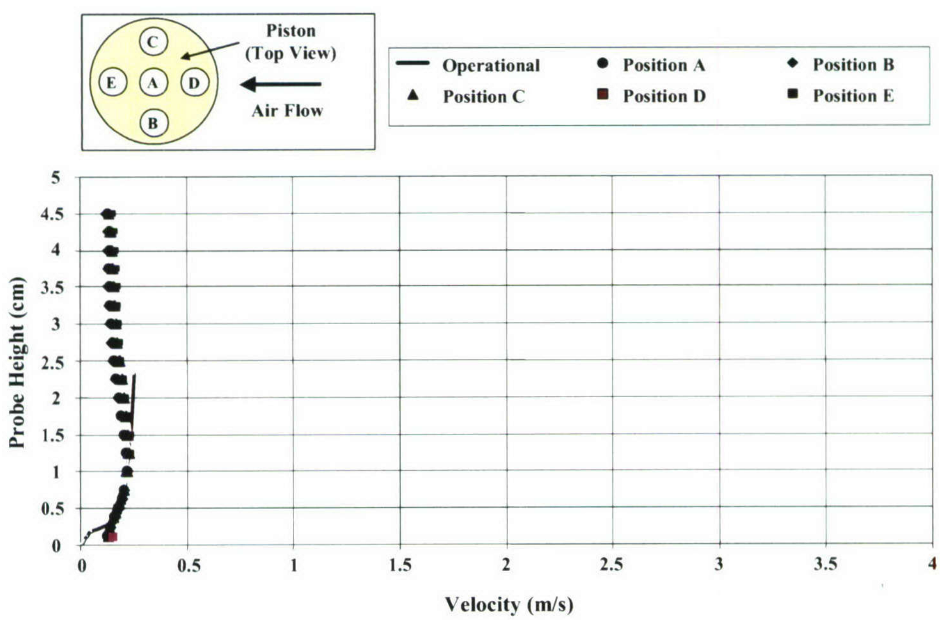


Figure 34. Tunnel 3B: Low Velocity

Figure 35 contains the vertical velocity profiles measured in tunnel 3B at all five positions for the medium velocity compared with the operational profile. The only notable deviation from the operational profile occurs at location B (lateral position closest to the test section window) where the velocities are slightly lower than the operational profile. However, even at this position, the measured profile is in close agreement with the operational profile in the critical region near the floor.

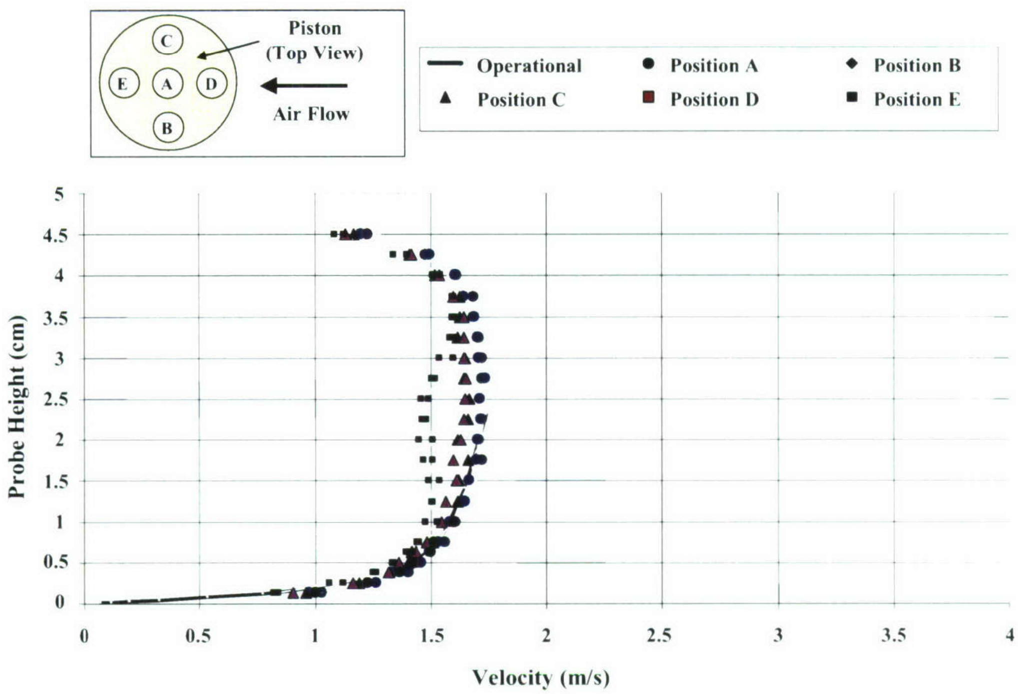


Figure 35. Tunnel 3B: Medium Velocity

Figure 36 contains the vertical velocity profiles measured in tunnel 3B at all five positions for the high velocity compared with the operational profile. In this case, the largest deviation from the operational profile occurs at positions B and C (lateral locations) where the velocities are consistently lower than the operational profile. This is most likely due to side wall effects. However, even at this position, the measured profile is in close agreement with the operational profile in the critical region near the floor. At a height of 1 cm, the difference in velocity is on the order of 5% and reduces as the profile approaches the test section floor.

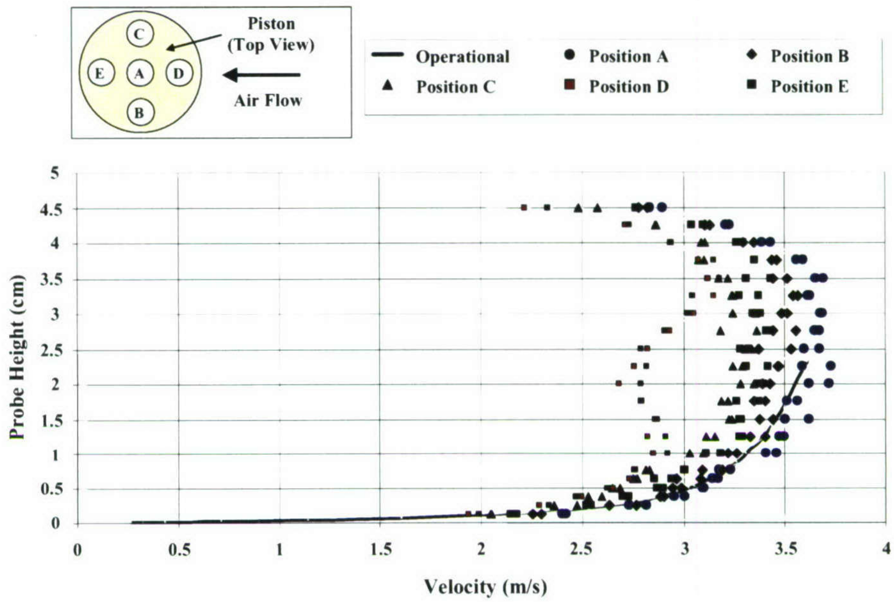


Figure 36. Tunnel 3B: High Velocity

5.4.2.3 Tunnel 3C

Figure 37 contains the vertical velocity profiles measured in tunnel 3C at the center position (position A) for all three velocities compared with their corresponding operational profiles. Good repeatability is present as well as close agreement with their operational profiles.

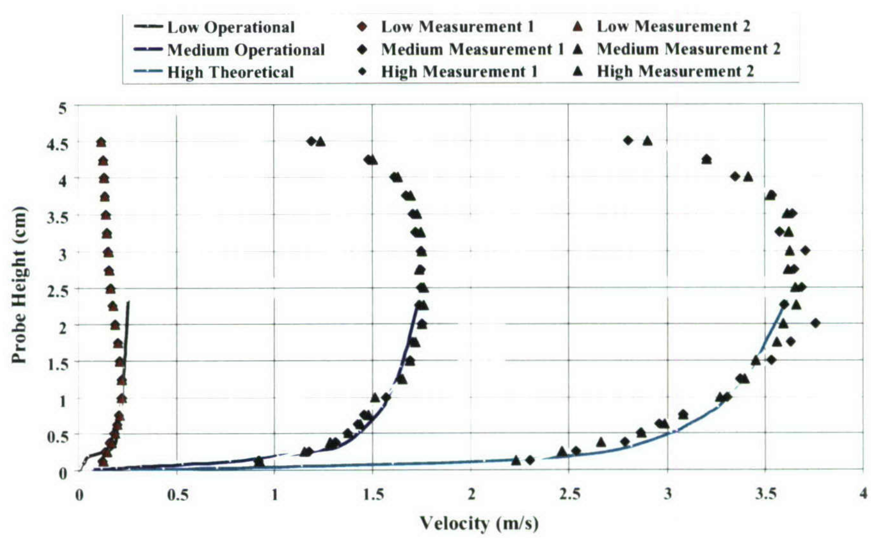


Figure 37. Measured Velocity Profiles for Tunnel 3C

5.4.2.4 Tunnel 3D

Figure 38 contains the vertical velocity profiles measured in tunnel 3D at the center position (position A) for all three velocities compared with their corresponding operational profiles. Good repeatability is present as well as close agreement with their operational profiles.

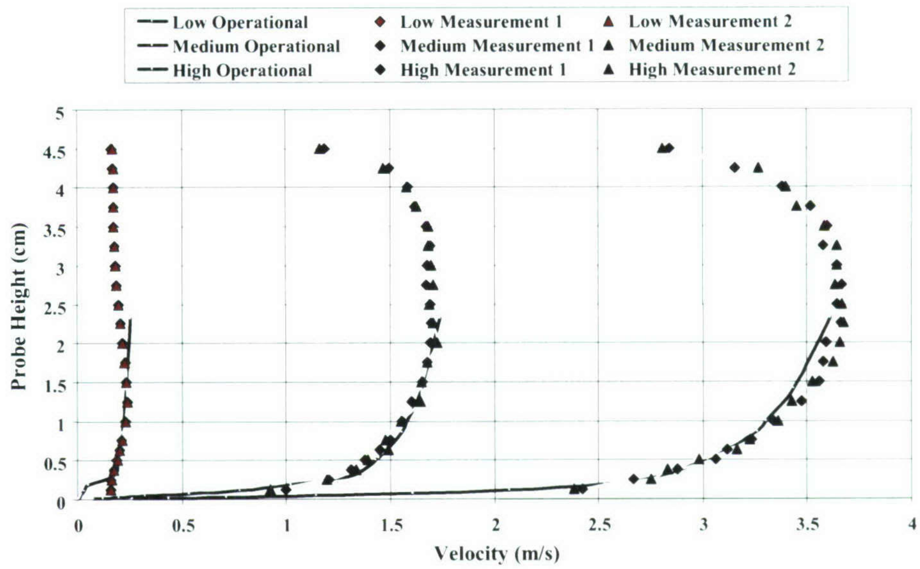


Figure 38. Measured Velocity Profiles for Tunnel 3D

5.4.2.5 Tunnel 3E

Figure 39 contains the vertical velocity profiles measured in tunnel 3E at the center position (position A) for all three velocities compared with their corresponding operational profiles. Good repeatability is present as well as close agreement with their operational profiles.

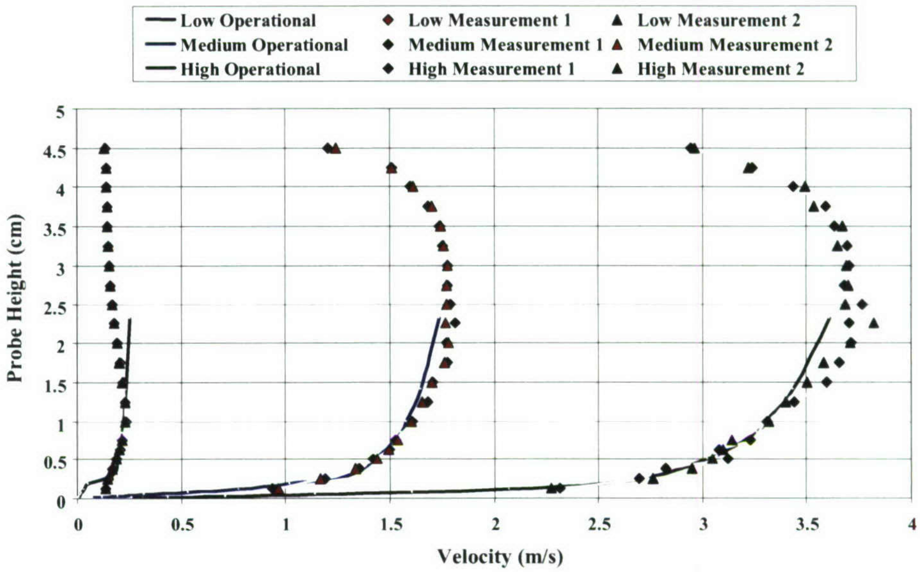


Figure 39. Measured Velocity Profiles for Tunnel 3E

5.4.2.6 Tunnel 3F

Figures 40, 41, and 42 contain the vertical velocity profiles measured in tunnel 3F at all positions for the low, medium, and high velocity, respectively, compared with their corresponding operational profiles.

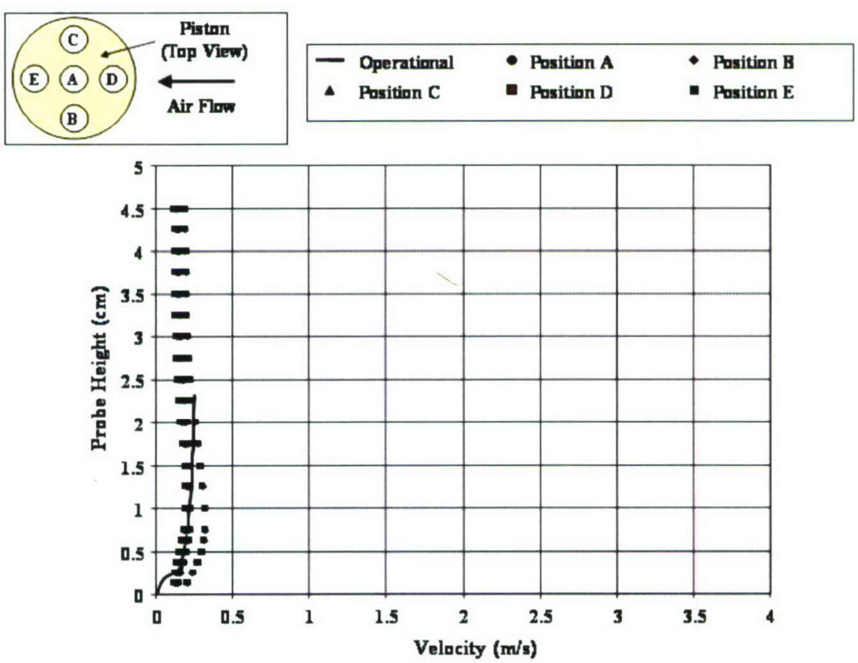


Figure 40. Tunnel 3F: Low Velocity

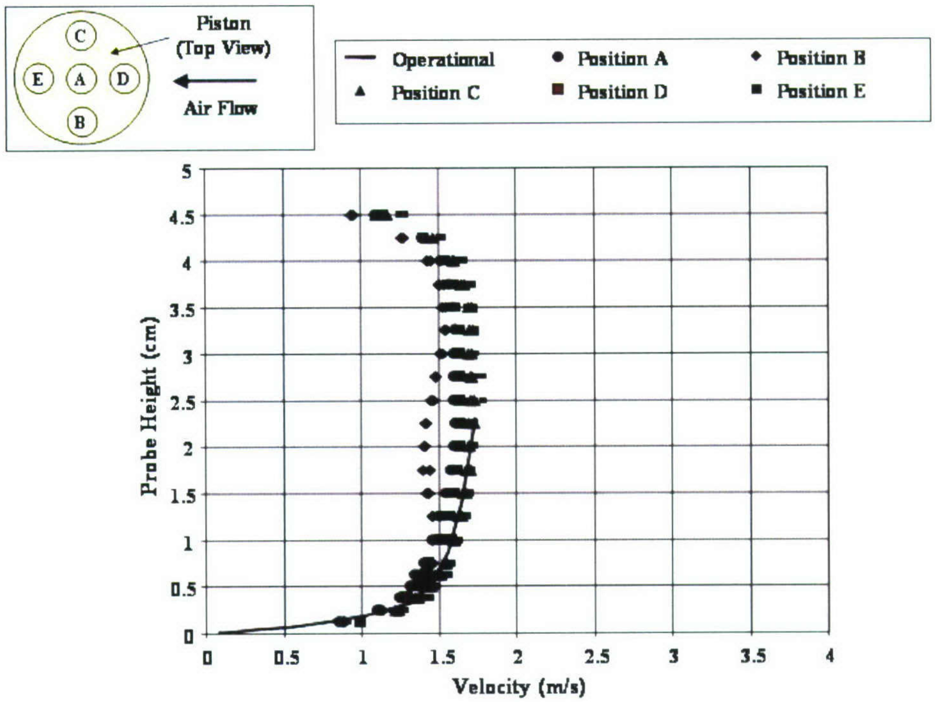


Figure 41. Tunnel 3F: Medium Velocity

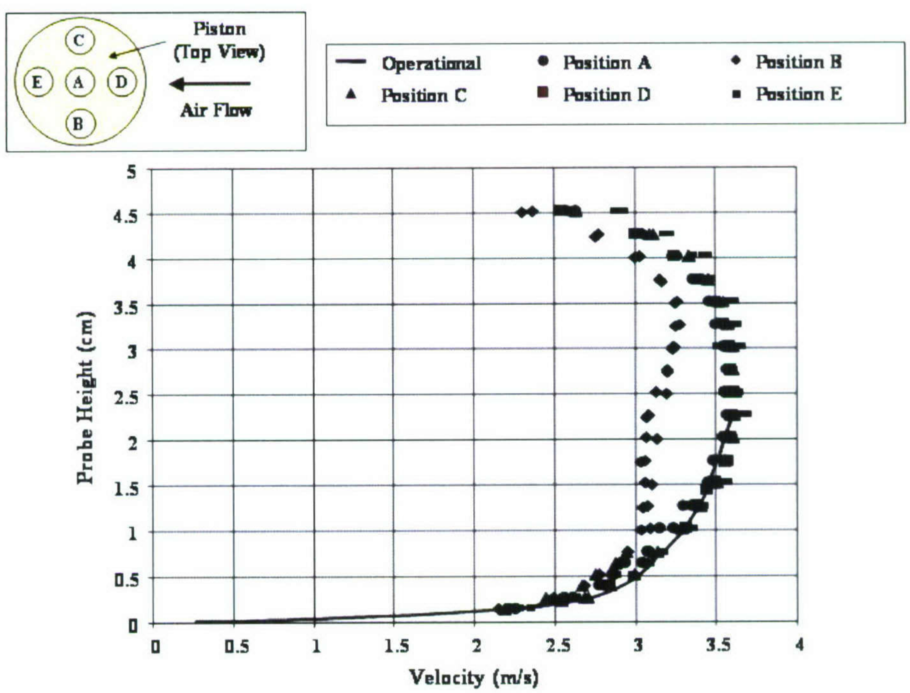


Figure 42. Tunnel 3F: High Velocity

5.4.3 Version 3 Mod 1

5.4.3.1 Tunnel 3G

Figure 43 contains the vertical velocity profiles measured in tunnel 3G at the center position (position A) for all three velocities compared with their corresponding operational profiles. This particular wind tunnel was converted from a Version 3 (horizontal transition cone and turning vane section) to a Version 3 Mod 1 (vertical transition cone and turning vane section). Velocity profiles were measured for both configurations. While differences in the measured profiles are noted between the two tunnel versions at the larger probe heights, they are essentially identical in the critical region near the test section floor. Good repeatability is present as well as close agreement with their operational profiles.

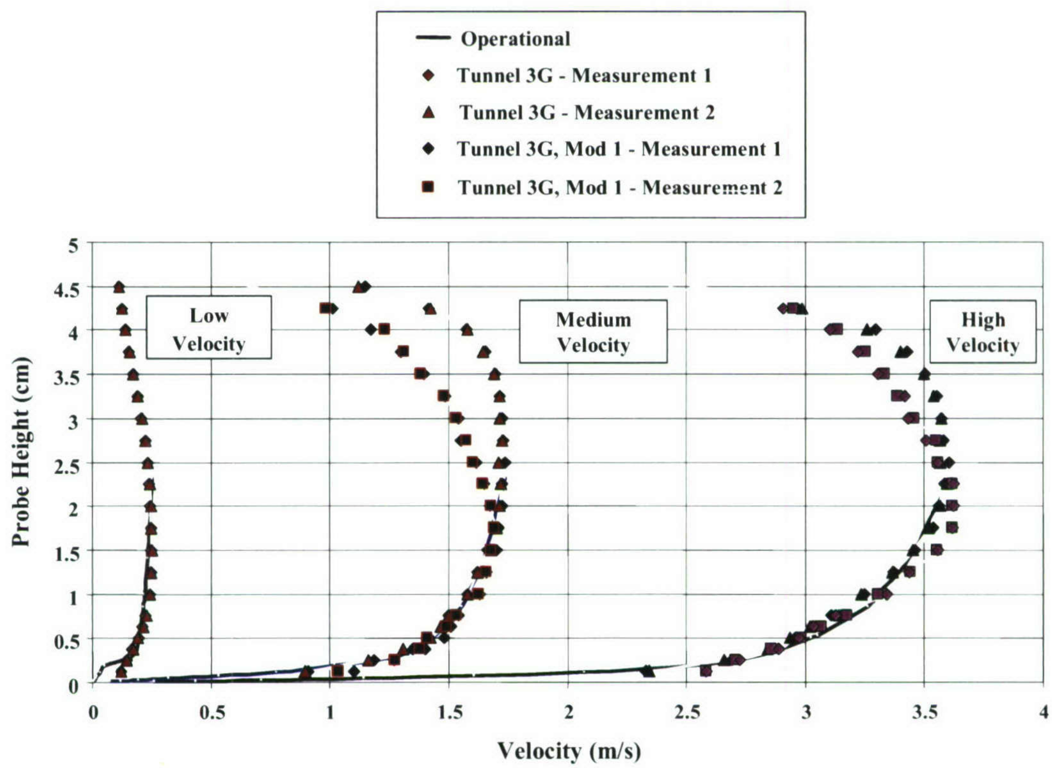


Figure 43. Measured Velocity Profiles for Tunnel 3G

5.4.3.3 Tunnel 3I

Figure 44 contains the vertical velocity profiles measured in tunnel 3I at the center position (position A) for all three velocities compared with their corresponding operational profiles. Good repeatability is present as well as close agreement with their operational profiles.

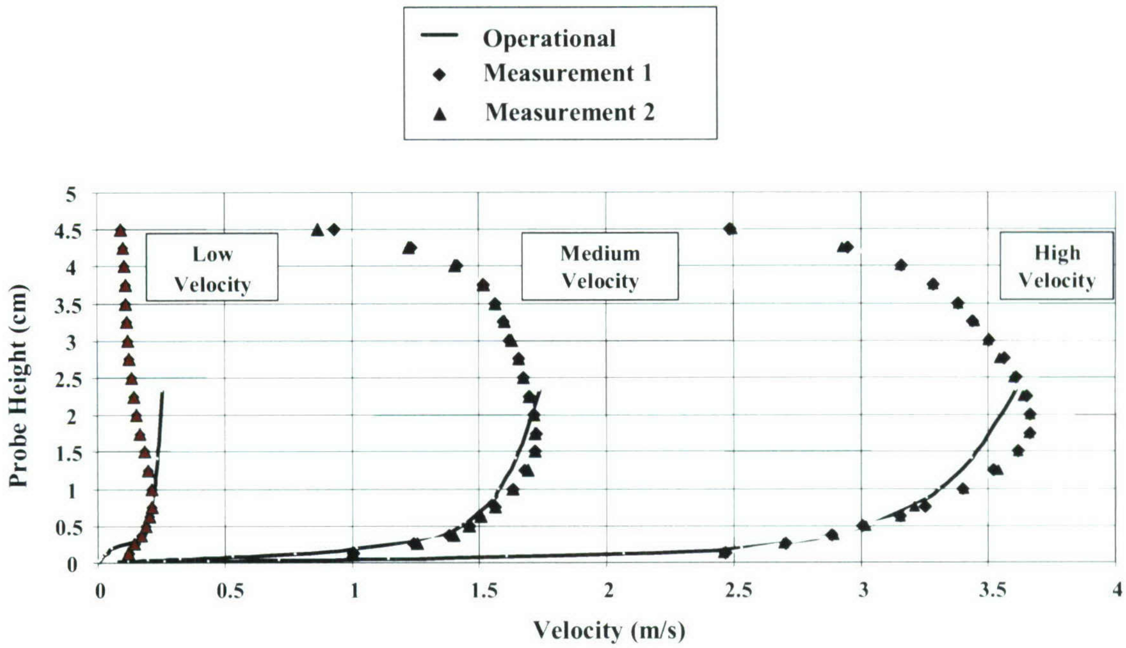


Figure 44. Measured Velocity Profiles for Tunnel 3I

5.4.3.4 Tunnel 3J

Figure 45 contains the vertical velocity profiles measured in tunnel 3J at the center position (position A) for the low and medium velocities compared with their corresponding operational profiles. Good repeatability is present as well as close agreement with their operational profiles.

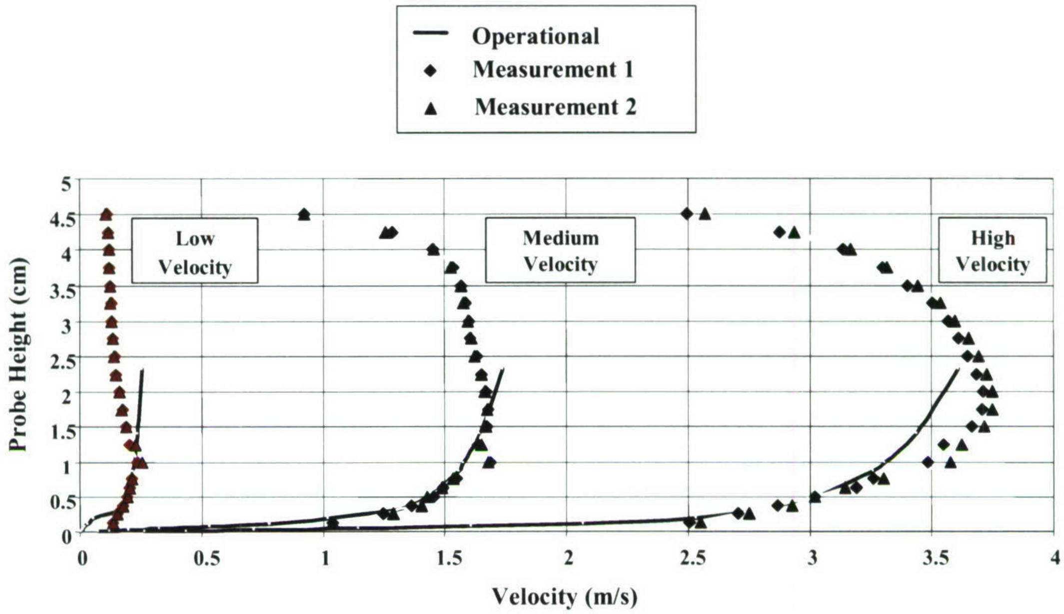


Figure 45. Measured Velocity Profiles for Tunnel 3J

5.4.3.5 Tunnel 3K

Figure 46 contains the vertical velocity profiles measured in tunnel 3K at the center position (position A) for the medium velocity compared with the corresponding operational profile. As noted previously, the vertical turning vane orientation of the Version 3 Mod 1 tunnel required the addition of a screen at the entrance to the fetch. As can be seen, the screen influences the profile near the center of the tunnel, but the velocity profile near the test section is unaffected and shows good agreement with the operational profile.

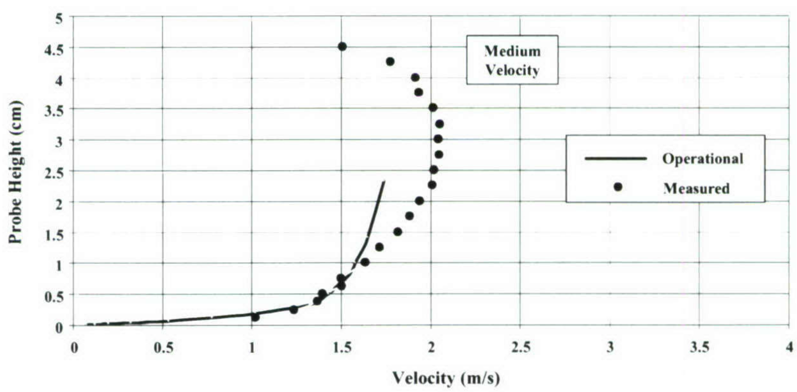


Figure 46. Tunnel 3K: Medium Velocity

5.4.3.6 Tunnel 3L

A complete velocity profile characterization was performed for tunnel 3L. Figure 47 contains the measured velocity profiles in tunnel 3L for all five positions at the low velocity condition. As was the case with the Version 3 tunnels, the profiles are invariant across the piston surface.

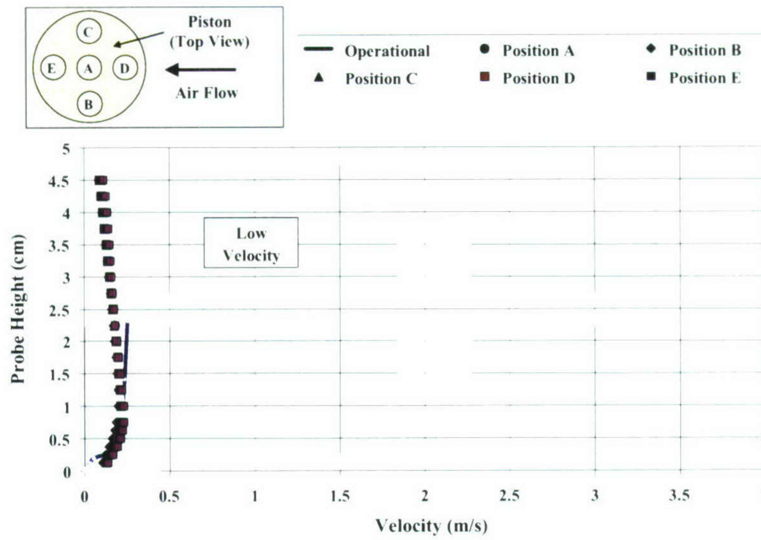


Figure 47. Tunnel 3L: Full Characterization of Low Velocity

Figure 48 contains the measured velocity profiles for all five positions at the medium velocity condition. The profiles are invariant across the piston surface and show good agreement with the operational profile.

Figure 49 contains the measured velocity profiles for all five positions at the high velocity condition. Here, the profile at position B (lateral position furthest from test section window) has slightly lower velocities toward the center of the tunnel but match the profile near the floor. The profile for Position E (downstream of the piston center) near the floor is slightly different from the operational profile. Again, the differences in velocities are only on the order of 5%. Otherwise, the profiles are invariant across the piston surface and show good agreement with the operational profile.

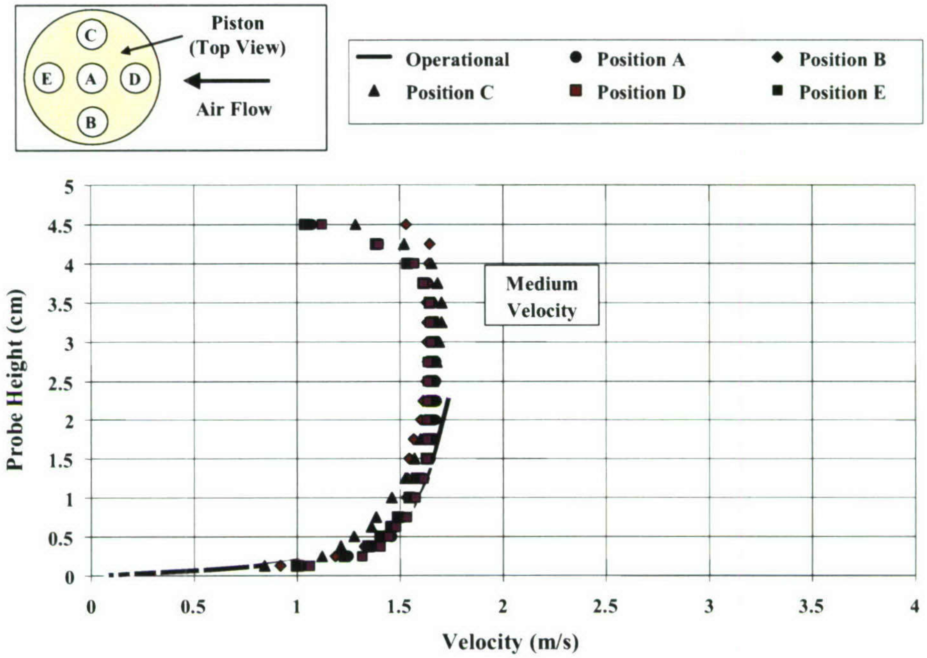


Figure 48. Tunnel 3L: Full Characterization of Medium Velocity

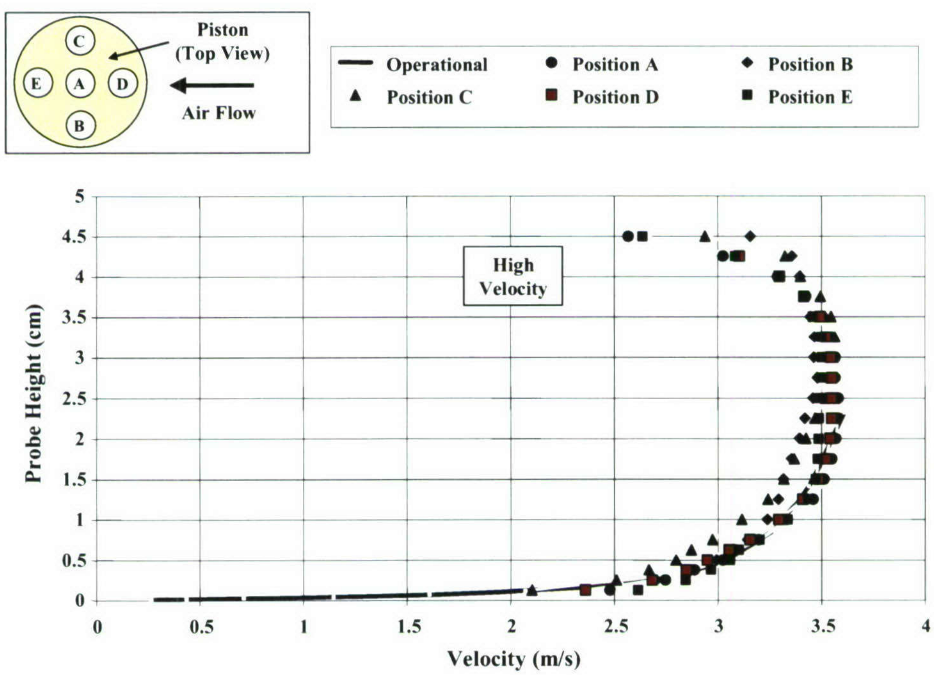


Figure 49. Tunnel 3L: Full Characterization of High Velocity Profile

5.4.4 Effect of Temperature

A series of experiments were performed in Tunnel 3F to evaluate the effect of air temperature on the vertical velocity profiles. For these tests, all of the tunnel heating elements were turned off which essentially produced an air temperature of 25 °C. Measurements were conducted at position A at the low and medium velocities. The resulting velocity profiles are shown in Figure 50 along with the profiles measured for the nominal 35 °C case as well as the operational velocity profiles. As can be seen, the air temperature had minimal effect on the profile.

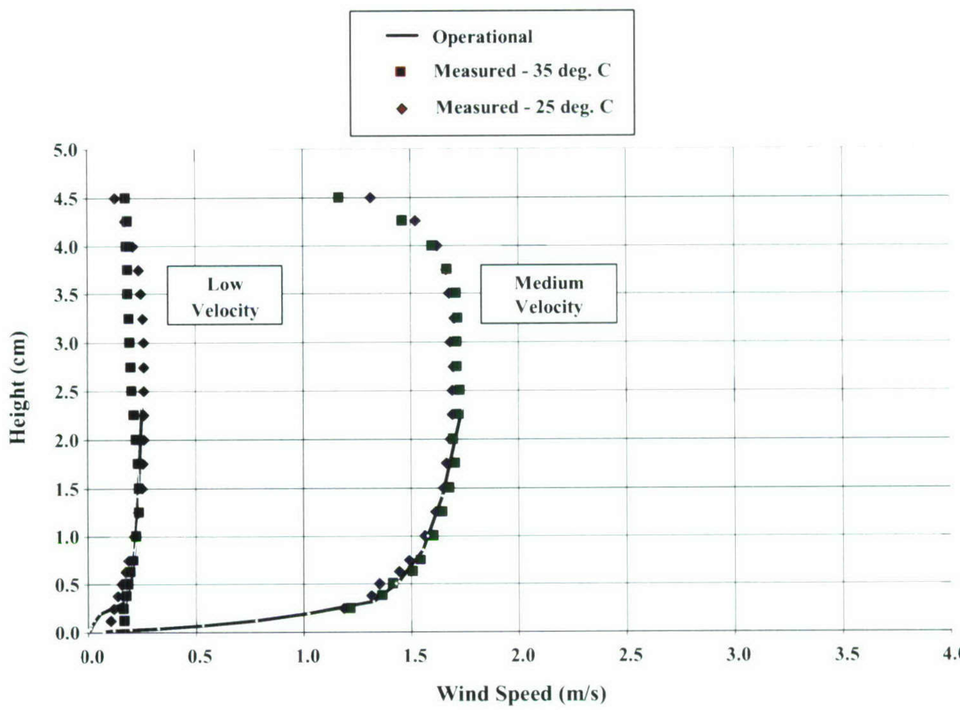


Figure 50. Effect of Air Temperature on Measured Velocity Profiles

5.4.5 Effect of Surface Roughness

Tunnel F was also used to evaluate the effect of surface roughness on the resulting vertical velocity profile. Two different concrete substrates were evaluated, each measuring 37.5 mm in diameter. Both had the same surface roughness relatively greater than glass. The concrete specimens were produced with a surface texture depth, to meet airfield concrete specifications for hydroplaning resistance. Two surface texture types were produced, a random brushed texture and a more uniform, ridged texture. The concrete studied possessed the ridged surface having a peak to trough dimension of about 0.5 mm and a peak to peak dimension of about 6.4 mm resulting in about 6 ripples across the diameter of the substrate samples. Vertical profiles were measured at the center of the substrate (position A) for the low and high velocities. Tests were performed with the concrete wave pattern oriented both in-line and normal to the air

flow direction. These profiles are shown in Figure 51 compared with their corresponding operational profiles. As can be seen, neither the increased roughness nor the orientation of the waves had any appreciable effect on the profiles.

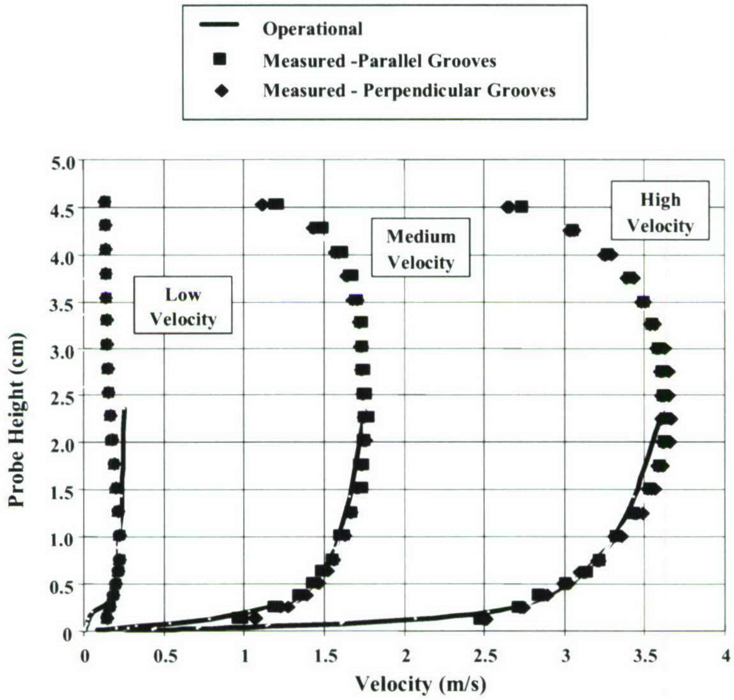


Figure 51. Effect of Concrete Groove Orientation Relative to Flow Direction

5.4.6 Effect of Inlet Screen

Tunnel K was the first Version 3, Mod 1 tunnel to be characterized. As noted previously, the vertical orientation of turning vanes with respect to the vertical velocity profiles in the test section required the use of an inlet screen at the entrance to the fetch. Tunnel K was used to develop the optimum screen configuration. Various screen porosities were evaluated and the results are also shown in Figure 52.

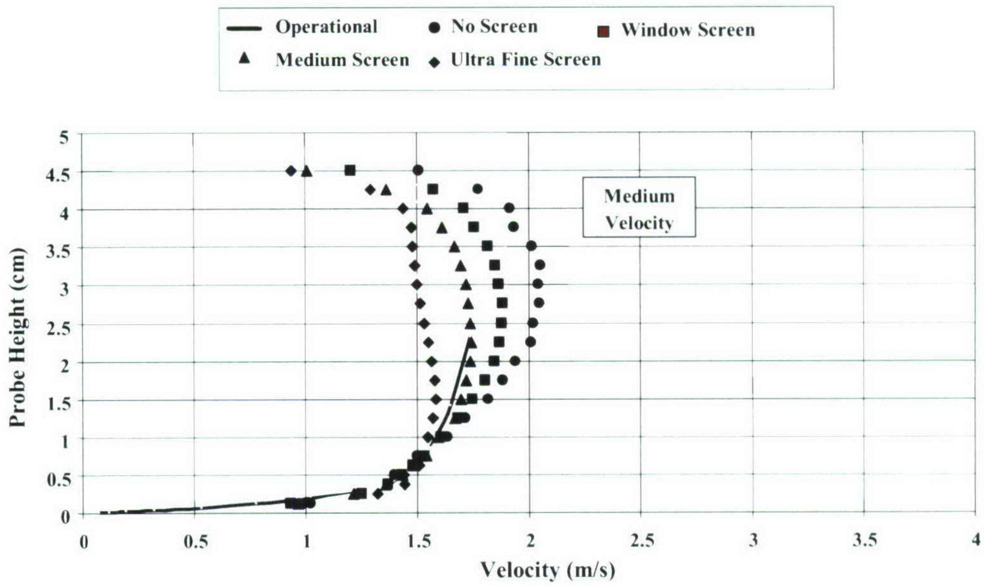


Figure 52. Effect of Screen

5.4.7 Consistency between Similar Tunnel Versions

Figures 53 and 54 compare vertical velocity profiles measured at the center position in five different Version 3 tunnels and three different Version 3 Mod 1 tunnels. In both cases, good consistency is achieved for both tunnel versions, especially in the critical lower region of the profiles near the test section floor. The extreme clustering of the data points is indicative of the good repeatability achieved for the velocity profiles among the different tunnels.

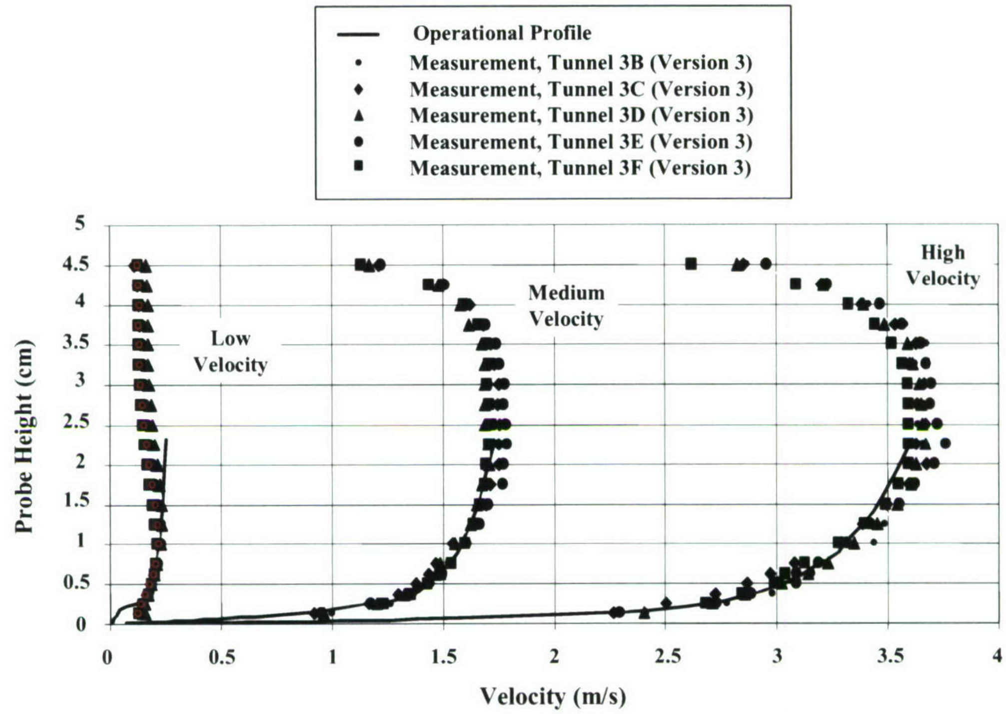


Figure 53. Consistency of Velocity Profiles in Version 3 Tunnels

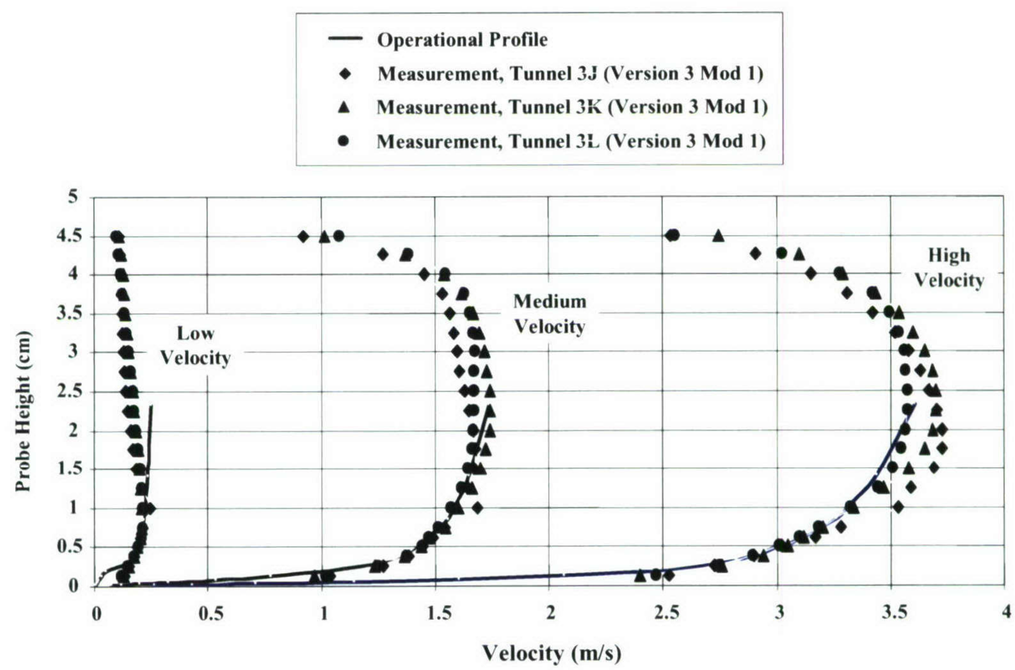


Figure 54. Consistency of Velocity Profiles in Version 3 Mod 1 Tunnels

5.4.8 Consistency between Different Tunnel Versions

Figure 55 compares the velocity profiles measured at the center position in the Version 3 and Version 3 Mod 1 configurations of the 5-cm Wind Tunnel. As can be seen, good agreement is present between the measured and operational velocity profiles in both versions of the wind tunnel.

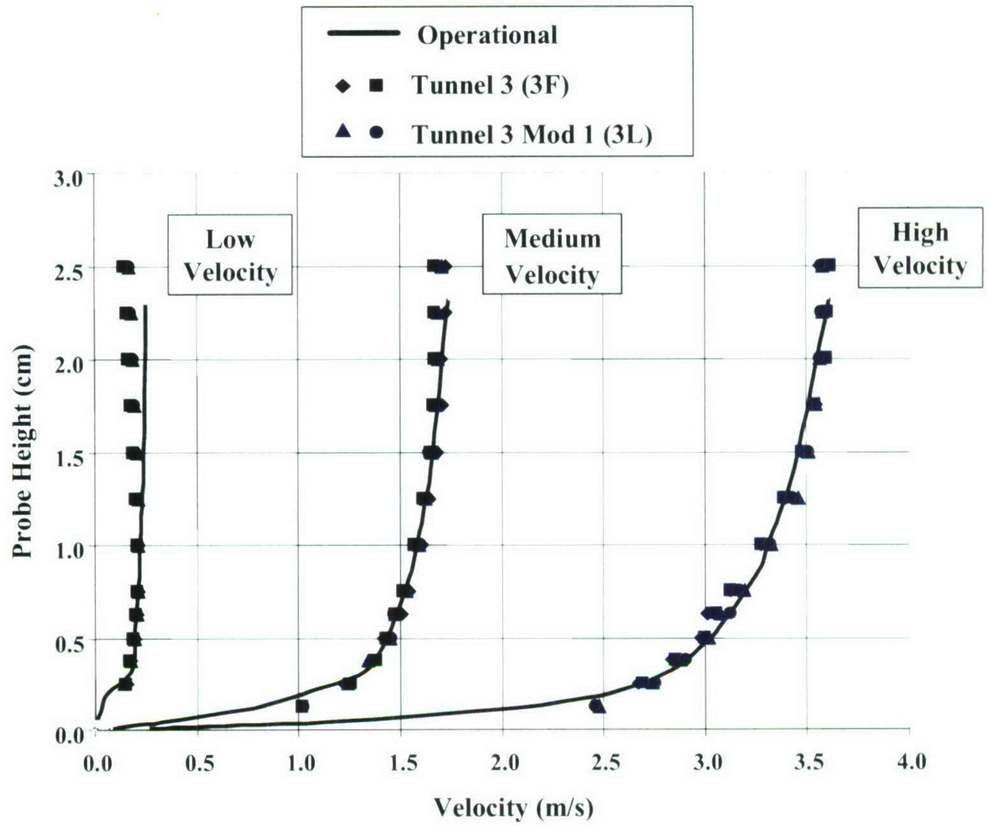


Figure 55. Velocity Profiles at Center Location for Tunnel 3 and Tunnel 3 Mod 1

6. FREE STREAM TURBULENCE

Free stream turbulence is the random, small magnitude velocity fluctuations occurring in any air stream, whether in an atmospheric boundary layer or in a wind tunnel. The 5-cm Wind Tunnel forces the creation of a turbulent boundary layer by introducing turbulence to the flow via the turbulence generators located at the entrance to the fetch section upstream of the test section. The formation of a turbulent boundary layer and its characteristic velocity profile depend on having a certain level of free stream turbulence present in the air flow (the more turbulence, the fuller the profile). However, its velocity profile (representing a specific friction velocity and a corresponding shear stress at the surface) is relatively insensitive to the free stream turbulence level as long as it remains within a certain range of values.

Free stream turbulence intensities were measured in the 5-cm Wind Tunnel for all tests. Representative turbulence intensities for each of the three velocity conditions are shown in Figure 56. Here the root mean square of the three orthogonal velocity fluctuations (due to turbulence) is referenced to the local total velocity. Thus, while the absolute free stream turbulence level is fairly constant throughout the tunnel, the intensity increases near the floor because the total velocity (the denominator in the turbulence intensity) decreases near the floor. As can be see, the turbulence intensity ranges from about 0.5 to 2% for the low velocity and about 4 to 14% for the medium and high velocities.

The turbulence level for the low velocity profiles indicates a laminar velocity profile. The flow lacks the inertia energy to overcome the viscous effects and develop a fully turbulent boundary layer. On the other hand, the medium and high velocity profiles contain sufficient inertia energy to develop a fully turbulent boundary layer profile. However, the free stream turbulence level in the wind tunnel does not affect the evaporation rates of the agents as long as the friction velocities are compatible.[2]

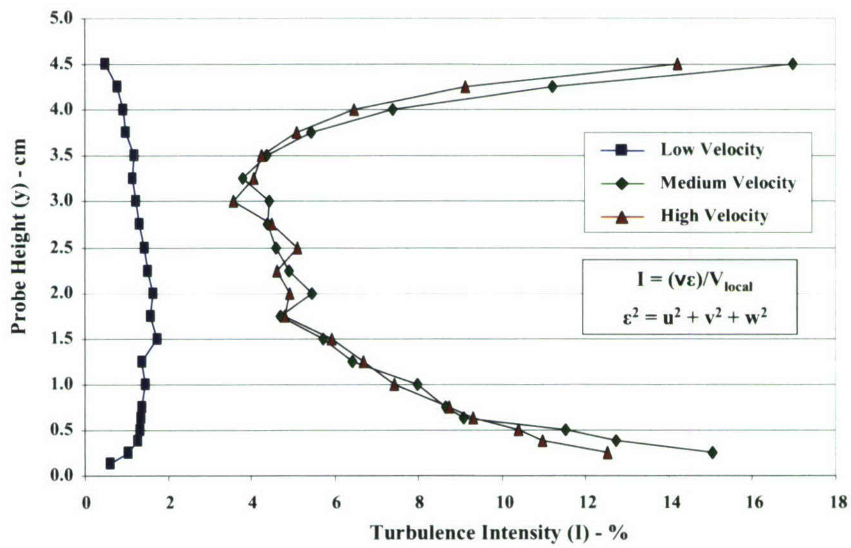


Figure 56. Turbulence Intensity of 5-cm Wind Tunnel

7. EXPERIMENTAL OPERATIONS

The test matrix* for the 5-cm Wind Tunnel includes the agents and substrates as well as the test parameters consisting of temperature, drop size, velocity and relative humidity.

The agents to be investigated are shown listed in order of their priority, based on importance to the program and feasibility of the measurements given their complexity:

HD
VX
GD
Thickened VX
Thickened GD

A key feature of the substrate was its interaction with the agent. The substrates were resolved into four basic categories:

1. non-absorptive, non-reactive
2. absorptive, non-reactive
3. non-absorptive, reactive
4. absorptive, reactive

Each agent might have specific substrates assigned to each category, depending mostly on its reactivity. The specific substrates to be tested were prioritized as follows along with their general substrate interaction characteristics noted above:

Substrate	Category
1. Glass	non-absorptive, non-reactive
2. Dry Sand/Clay	absorptive, non-reactive
3. Concrete	absorptive, reactive
4. Asphalt	absorptive, reactive
5. Grass	absorptive, reactive

A series of validation tests were performed involving HD on glass (glass representing a non-absorbent, non-reactive substrate for HD). With the "Validation" tests completed, the program then entered the "production" testing phase. This involves testing agents with the more complex substrates. The initial production tests involved HD on sand. Each combination of agent and substrate were tested at each of the three velocity conditions, three temperatures and, if relevant, three relative humidity values as presented in Figure 57.

* Kilpatrick, W. T.; Ling, E. E.; Hin, A. R. T.; Brevett, C. A. S.; Fagan, M. W.; Murdock, W. P. Jr. *Testing Requirements for Predictive Model Development Using Environmental Wind Tunnels*. Air Force Research Laboratory: Wright-Patterson Air Force Base, OH, submitted for publication.

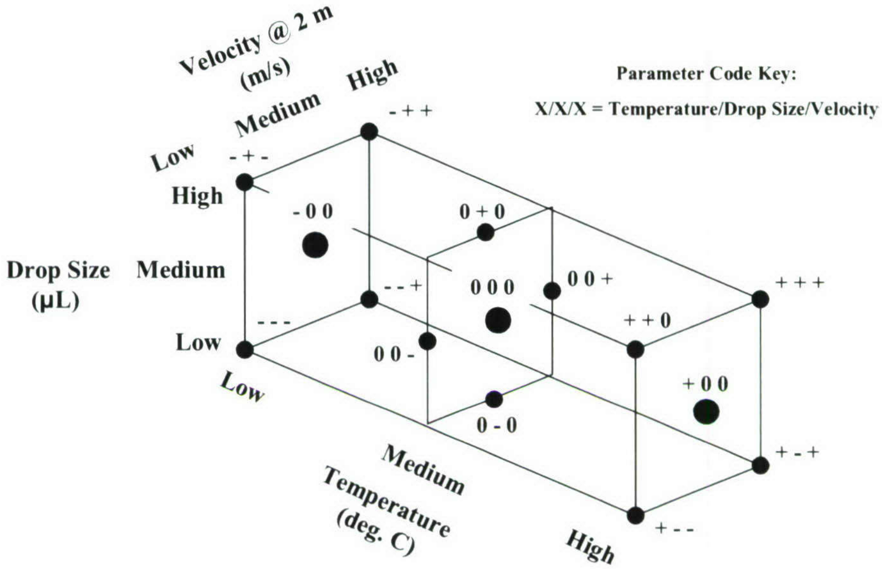


Figure 57. Basic Test Matrix Arrangement and Coding*

8. EVALUATION OF 5-CM WIND TUNNEL VELOCITY PROFILES

8.1 Overview Evaluation

An analysis was performed[9] to evaluate how well the experimental velocity profile measurements in the 5-cm Wind Tunnel agree with the operational profiles specified by the Agent Fate program and the effect of any differences on the subsequent agent evaporation measurements.

8.2 Turbulent Boundary Layer, Log-Law, and Law-of-the-Wall Variables

Fully developed boundary layers or internal flows include a region identified as the logarithmic-layer where the velocity profile can be represented by:

$$\frac{u}{u_\tau} = \frac{1}{\kappa}\ln\left(\frac{u_\tau y}{\nu}\right) + C \qquad (1)$$

* Kilpatrick, W. T.; Ling, E. E.; Hin, A. R. T.; Brevett, C. A. S.; Fagan, M. W.; Murdock, W. P. Jr. *Testing Requirements for Predictive Model Development Using Environmental Wind Tunnels*. Air Force Research Laboratory: Wright-Patterson Air Force Base, OH, submitted for publication.

Where:

u = velocity parallel to the surface
y = distance normal to the surface
ν = kinematic viscosity
κ = von Karman Universal Constant of Turbulence ($\kappa \cong 0.4$)
u_τ = friction velocity ($u_\tau = \sqrt{\frac{\tau_w}{\rho}}$)
τ_w = stress acting on surface
ρ = air density
$C = 5.5$ (fully developed, turbulent boundary layer on a flat plate with a zero pressure gradient)

A Fortran program was developed to take three or more data points from the measured profile and to perform a linear least squares fit to u versus ln(y) to compute the slope and, assuming $\kappa = 0.4$, to determine the most likely value of u_τ and the intercept C. The initial points were selected by trial and error but usually excluded the 2 or 3 points nearest the floor and the points beyond the centerline of the tunnel which deviated from the linear. Most of the primary profile measurements were made at the center of the test section (Position A) and were repeated up to three times and these runs were grouped together. The numerical data were transferred to a plotting routine where the least square fits were compared with the data.

As noted previously, a set of operational velocity profiles were defined for the Agent Fate Wind Tunnels representing wind velocities of 0.5, 3.0, 6.0 m/s at a height of 2 m above the ground. It is assumed that the smooth wall equilibrium turbulent boundary layer exists within the 2 m. The previous equation was used to determine the associated friction velocities and the velocities at a 2-cm height for the three operational velocity profiles with $\kappa = 0.4$ and $C = 5.5$.

Table 4. Extrapolated Operational Velocities to 2-cm Height

Velocity (m/s) @ 2 m	u_τ, Friction Velocity (m/s)	Velocity (m/s) @ 2 cm
0.5	0.020	0.26
3.0	0.1038	1.79
6.0	0.1966	3.70

The boundary layer profile can also be expressed in terms of no-dimensional "law of the wall" coordinates (u^+ and y^+):

Where:

u^+ = Law of the wall velocity coordinate = u/u_τ

u_τ = Friction or shear velocity = $\sqrt{\upsilon(\partial u/\partial y)_w}$
y^+ = Law of the wall height coordinate = $u_\tau y/\upsilon$

$(\partial u/\partial y)_w$ = velocity gradient at surface ($y = 0$)

A hot wire anemometer was used to measure the velocity profiles and the turbulence intensity distribution in the 5-cm Wind Tunnels. These include two slightly different configurations: one having a horizontal inlet and the other having a vertical inlet. Velocity profiles were measured at the center of the test section for three velocity conditions. These are designated as high, mid and low for the 2 m height values for the operational velocities of 6, 3, and 0.5 m/s, respectively. Selected points are shown in "law of the wall" coordinates in Figure 58. As can be seen, for the low speed case, the range of the measurements are within the transition region and do not extend into the log-law region. Whereas the high-speed case is entirely within the log-law and the mid speed is predicted to have a substantial range in the log-law but with the lower points extending into the transition region.

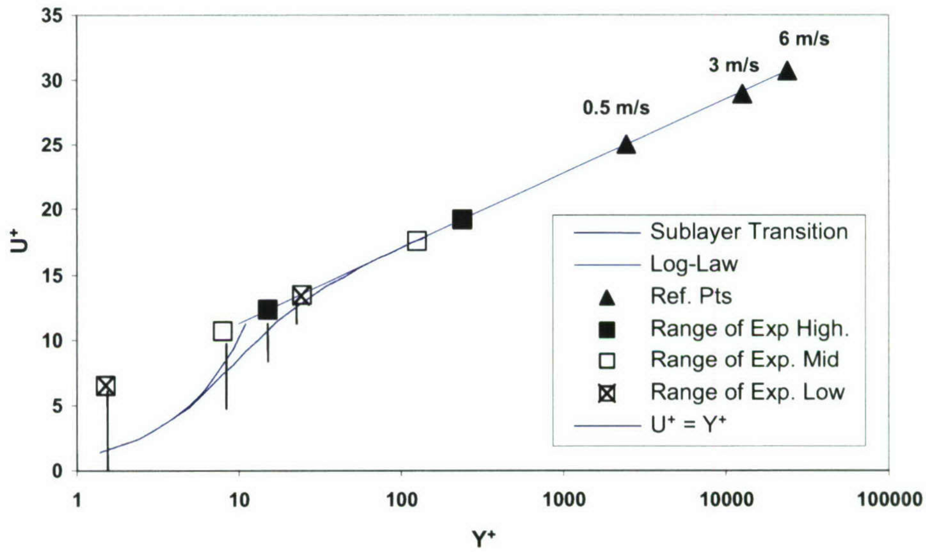


Figure 58. Non-dimensional Velocity Profile

8.3 Mid and High Velocities

Two series of profile measurements are considered representing the horizontal inlet configuration with no inlet screen (T3B) and the vertical inlet configuration with the standard 44% porosity screen (T3L). The friction velocity defines the near-wall velocity distribution for a smooth wall and the specification of the velocity at 2 m along with the assumed profile form (Log-Law) defines the friction velocity. The friction velocity was determined from the slope of u versus ln(y) assuming the von Karman universal constant of turbulence $\kappa = 0.4$. A linear least squares technique was used with 3-7 data points identified as falling in the linear range. Figure 59 illustrates the quality of the fit.

Figures 60 and 61 present the measured velocity profile values in non-dimensional form compared with the operational profiles. As can be seen, in both cases, the measurements are higher than the operational values but the slopes are in general agreement.

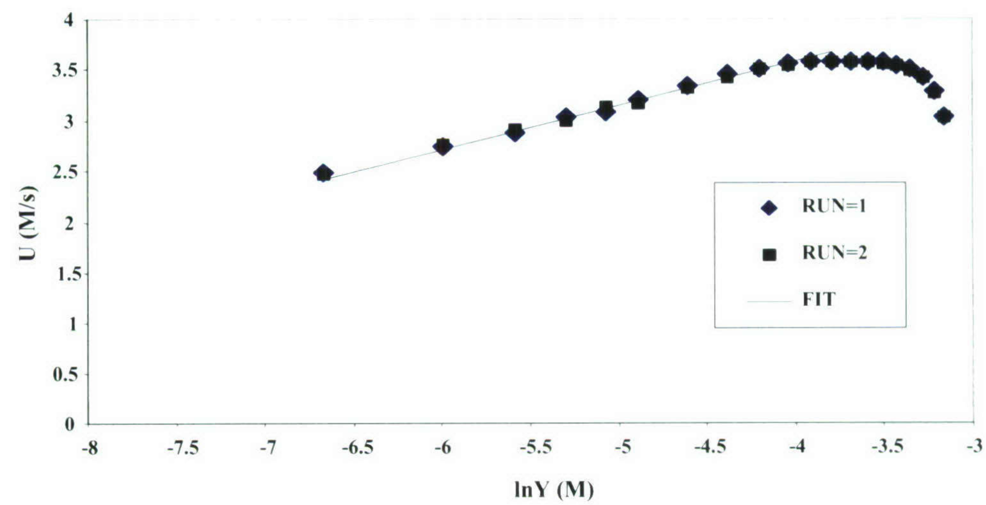


Figure 59. Log-Law Slope (Tunnel T3L)

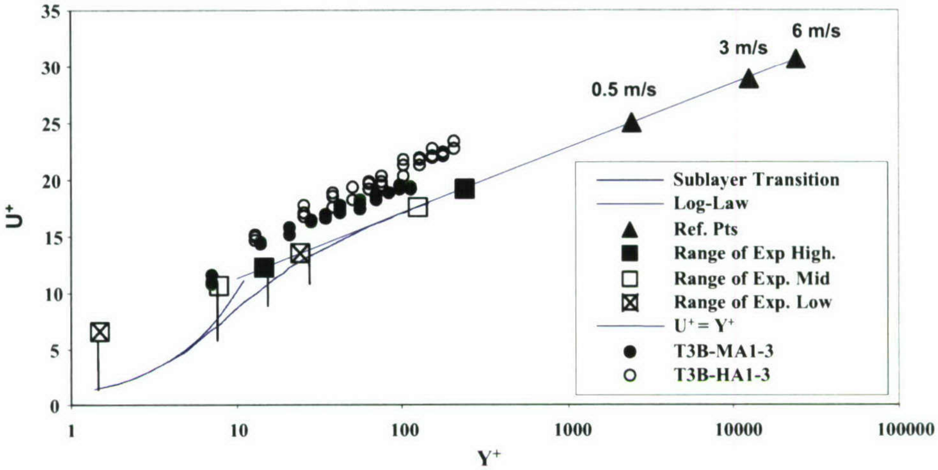


Figure 60. Measured vs. Operational Velocity Profile Values of Tunnel T3B

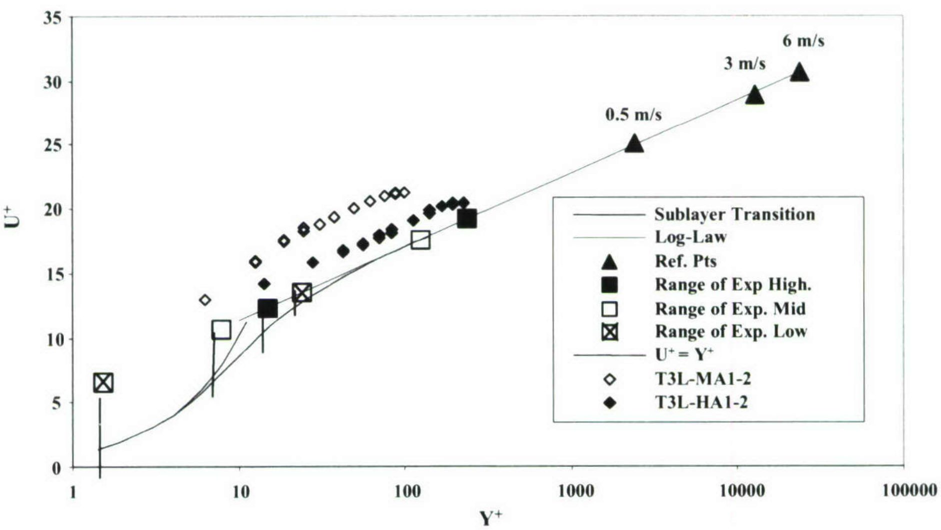


Figure 61. Measured vs. Operational Velocity Profile Values of Tunnel T3L

The shift in the measurements relative to the operational curve is reflected in the intercept C obtained from the least square fit. Since there is no trend with velocity in these data, an overall average of $C = 8.5 \pm 1.0$ describes the data whereas the assumed value for the operational profile is $C = 5.5$. There could be several causes for this modification of the profile from the normal including: a departure from the two-dimensionality condition because of sidewall effects due to the small scale of the facility; the inlet flow moving through a 90° bend prior to entering the fetch; and the unsymmetrical surface roughness created by the turbulence generators located only five test section heights upstream of the test section.

Not all the profiles investigated show such a large value for the intercept C. A more complete picture can be gained from Table 1 where friction velocity and C are presented for fifteen profiles measured in different 5-cm Wind Tunnels. The average of all the runs is $C = 6.6$ and $u_\tau = 0.180$ and 0.096 for the high and mid velocities respectively. Using these results it is possible to work back to obtain the velocity at 2 m for the average measured profile, i.e., $u_{2m} = 5.7$ and 2.9 m/s, which differ only slightly from the operational values.

Table 5. Friction Velocity Data Obtained from Measured 5-cm Wind Tunnel Profiles

RUNS	u_τ m/s	$2\sigma\ u_\tau$ %	C	COMMENT
T3B-HA1-3	0.160	23	9.2	Horiz. Inlet, No Screens
T3F-HA9-10	0.202	6.0	4.5	Horiz. Inlet, No Screens
T3G-HA3-4	0.189	3.7	5.2	Horiz. Inlet, No Screens
T3F-HA11-12	0.188	6.0	5.8	Horiz. Inlet, No Screens
AVERAGE	0.184		6.2	
T3L-HA1-2	0.174	8.3	7.2	Vert. Inlet, 44% Porosity Screens
Table 5. Friction Velocity Data Obtained from Measured 5-cm Wind Tunnel Profiles (Continued)				
RUNS	u_τ m/s	$2\sigma\ u_\tau$ %	C	COMMENT
T3EYE-HA3-4	0.201	4.3	4.7	Vert. Inlet, 44% Porosity Screens
T3K-HA8-9	0.158	6.4	9.4	Vert. Inlet, 44% Porosity Screens
AVERAGE	0.178		6.9	
T3G-MA1-2	0.096	5.4	6.1	Horiz. Inlet, No Screens
T3F-MA5-6	0.103	9.3	5.2	Horiz. Inlet, No Screens
T3F-MA7-8	0.108	7.6	4.3	Horiz.Inlet, No Screens
T3B-MA1-3	0.088	17	7.9	Horiz. Inlet, No Screens
T3F2-MA2	0.102	13.1	5.4	Horiz. Inlet, No Screens
AVERAGE	0.100		5.6	
T3K-MA6-7	0.099	6.8	5.8	Vert. Inlet, 44% Porosity Screens
T3L-MA1-2	0.078	8.3	10.2	Vert. Inlet, 44% Porosity Screens
T3EYE-MA1-2	0.099	5.6	6.08	Vert. Inlet, 44% Porosity Screens
AVERAGE	0.092		7.4	

Figure 62 presents the T3B experimental data in physical variables and a semi-logarithmic format and includes the operational profile which is computed based on the mixing length analysis the $u^+ = y^+$ line referred to the friction velocity.

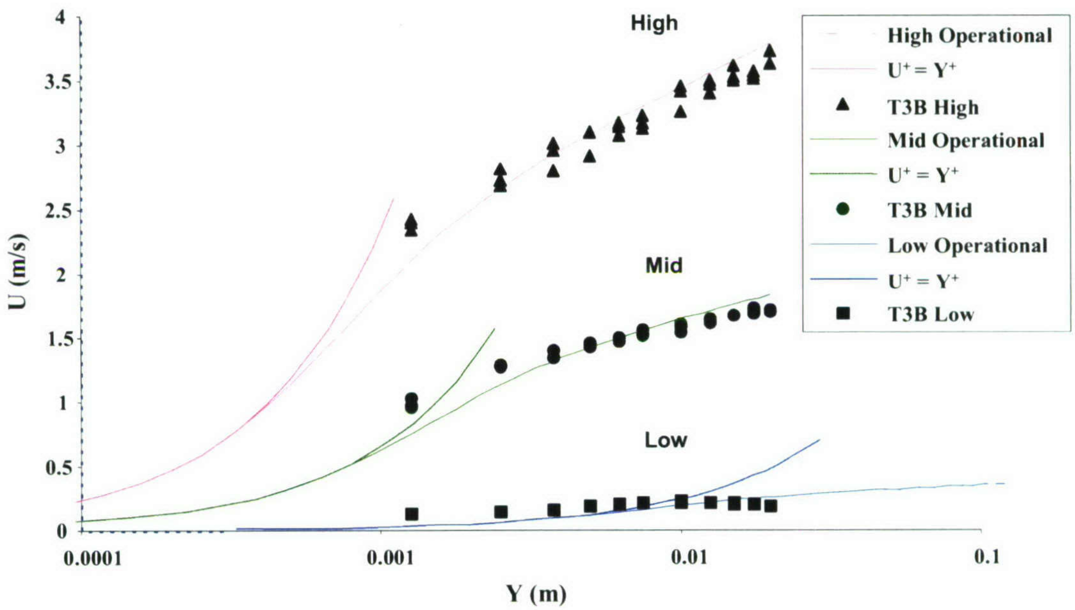


Figure 62. Semi-Logarithmic T3B Profiles vs. Operational Profile

The velocity at a height of 2 cm was initially used as the reference value for the 5-cm Wind Tunnel validation tests involving HD on glass. The reference velocity for the follow-on production tests was later changed to that at a 1-cm height. Table 5 shows how well the velocities measured at both reference heights in four different 5-cm Wind Tunnels compared with the associated operational values.

Thus, the measured velocity at a 2-cm height is about 5-7% lower than the operational velocity with an average difference of 3.9% and a standard deviation of 1.3%. The measured velocity at an 1-cm height 4 to 5% lower than the operational velocity with an average of 4.0% with a standard deviation of 1.3%. The least square fit u_{2cm} agrees closely with the experimental data which again shows that the data and fit diverge somewhat from the operational profile.

Table 6. Comparison of Measured and Operational Velocities at 1- and 2-cm Heights

Tunnel/Run	Operational Profile (m/s)	Measured Profile (m/s)	Difference %	LS Fit Profile (m/s)
		Velocities at 1 cm		
T3B-HA1-3	3.45	3.37	-2.2	3.32
T3L-HA7-8	3.45	3.33	-3.6	3.30
T3B-MA1-3	1.66	1.58	-4.7	1.58
T3L-MA1-2	1.66	1.57	-5.2	1.59
		Velocities at 2 cm		
T3B-HA1-3	3.69	3.66	-0.8	3.57
T3L-HA7-8	3.70	3.57	-3.6	3.62
T3B-MA1-3	1.80	1.71	-5.0	1.74
T3L-MA1-2	1.79	1.67	-6.7	1.71

8.4 Low Speed Velocity

The low velocity data would be expected to fall, for the most part, in the transition or buffer region between the laminar sub layer and the fully turbulent or the log-law region. Thus, the analysis of the [low velocity] profile assuming a semi-logarithmic region is not applicable as it is for the higher [two] velocities. The measurements extended sufficiently near the wall so that the velocity gradient at the wall is obtained by extrapolation and thus the wall shear stress and the friction velocity can be determined. The existing computer code was modified to skip the log-law analysis and perform the extrapolation in the following form

$$u = Ay + By^2 + Cy^3 \qquad (2)$$

In this form the boundary condition $u \to 0$ as $y \to 0$ is automatically satisfied. To actually carryout the fitting of the data to determine the coefficients, the data were put into the form of u/y vs. y or

$$\frac{u}{y} = A + By + Cy^2 \qquad (3)$$

The results showed that the data point closest to the wall had to be excluded in order to obtain anything like a monotonic fit and then only a limited number of profile data points could be used. The shape of the measured profile is more complicated than can be described by such a simple formula without introducing inflections in the fitted curve. The resulting T3L and T3B data are shown in Table 6.

Table 7. Low Velocity Profile Analysis Results

Tunnel	From Data			Operational
	u_τ (m/s)	δ (m)	u_δ (m/s)	u_τ (m/s)
T3L	0.0396	0.011	0.221	0.02
T3B	0.0390	0.010	0.216	0.02

The ability of the quadratic fit to describe the near wall points for the T3L case is shown in Figure 63 compared with the operational profile.

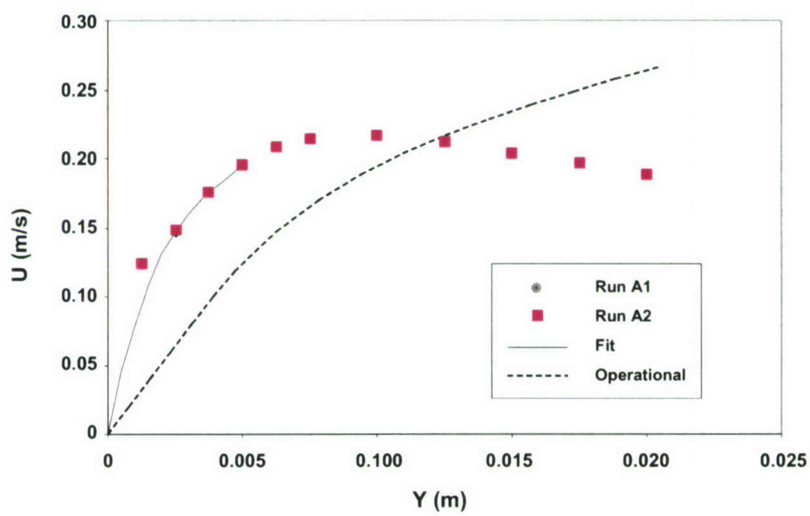


Figure 63. Experimental vs. Operational Low Speed Velocity Profiles

The friction velocity calculated by the above procedure is a factor of two larger than the operational profile. It is difficult to see how the existing data could be extrapolated to the wall with a wall slope as small as required (by a factor of 2.) Linearly extrapolating the next to the last data point gives a value of $u_\tau \cong 0.03$ that is still 50% larger than the Operational prediction. It is possible that the hot wire anemometer data at this low velocity could be contaminated by wall interference. Assuming the u_τ obtained in this way allows the profile to be plotted in the law of the wall coordinates as shown Figure 64. In these coordinates the data fall well below the sub layer $u^+ = y^+$ line and the empirical buffer layer line.

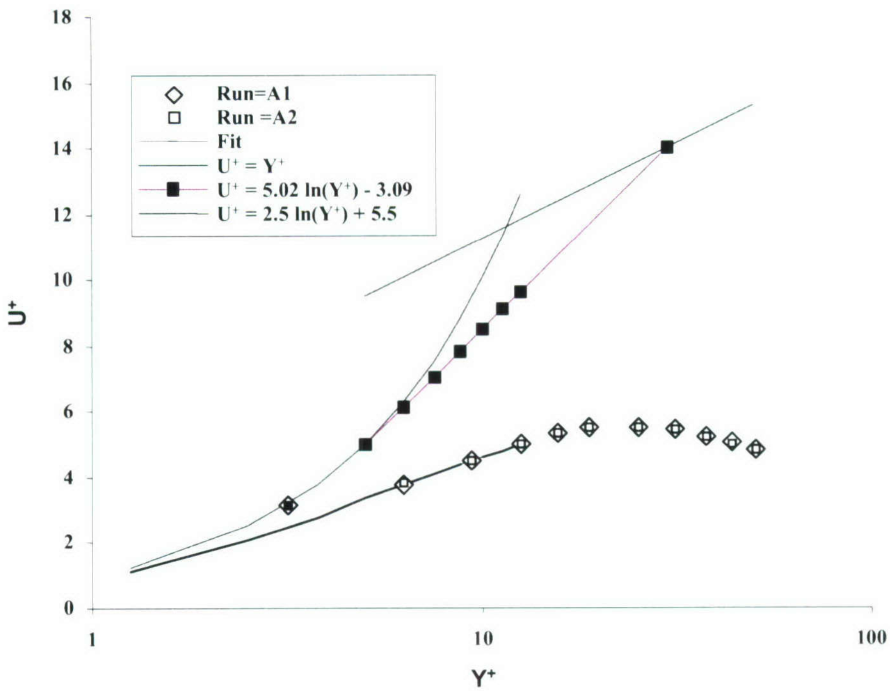


Figure 64. Low Velocity "Law of the Wall" Coordinates

The deviation from the buffer layer distribution in the law of the wall coordinates does not correspond to the desired turbulent profile. It appears appropriate to consider the low speed data to be a laminar boundary layer with some imposed turbulence from the tripping elements. The friction velocity correlates with that of a laminar boundary layer just as well as for the turbulent boundary layer. Thus, u_τ represents the characteristic convection velocity for the laminar evaporation just as well as for the turbulent flow. For the same u_τ a laminar boundary layer may be expected to produce the same evaporation rate as long as the concentration distribution in the vicinity of the drop is not affected by the turbulence away from the fluid surface. Thus, the low speed velocity condition is quite different from that of the higher two velocities and may be considered to represent a "very low" wind speed case.

8.5 Turbulence Intensity Measurements

Turbulent intensity measurements were obtained in the form of root-mean-square stream-wise fluctuations. In order to emphasize the sub layer, the data are re-normalized by the friction velocity rather than the local velocity. The turbulent intensity data were converted using $u'^{+} = \frac{u'}{u} u^{+}$ and the results for selected profiles are compared in Figure 65. The T3B data refer to a horizontal inlet tunnel without screens while the vertical inlet, T3K tunnel has inlet screens of 61 and 44% porosity. As might be expected the turbulence intensity decreases with decreasing screen porosity.

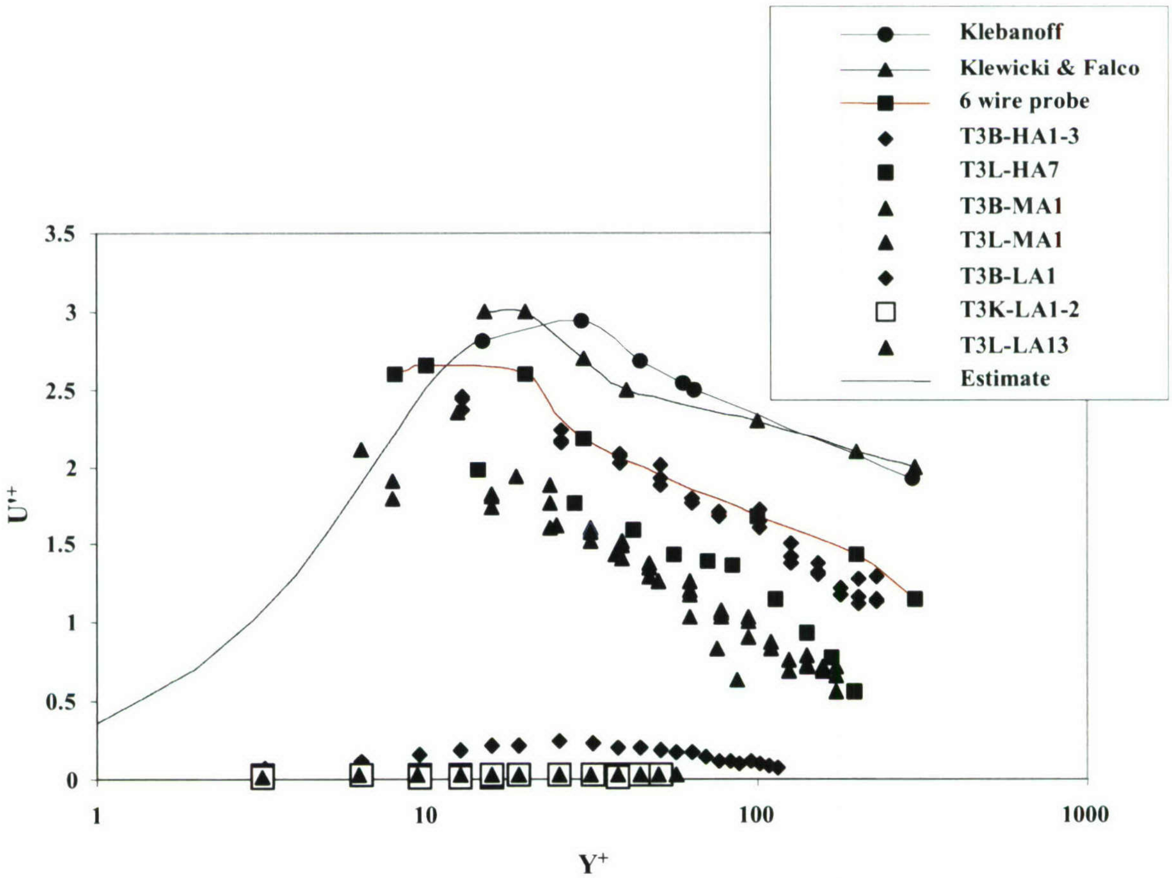


Figure 65. Comparison of Turbulence Intensities

Figure 66 provides examples of the wall layer turbulence level for all three velocities. The maximum of the low velocity intensity data normalized by the friction velocity is more than a factor of 100 less than the mid and high velocity cases for most of the runs. This provides additional evidence that the low velocity data should be considered laminar and treated differently than the higher velocity data.

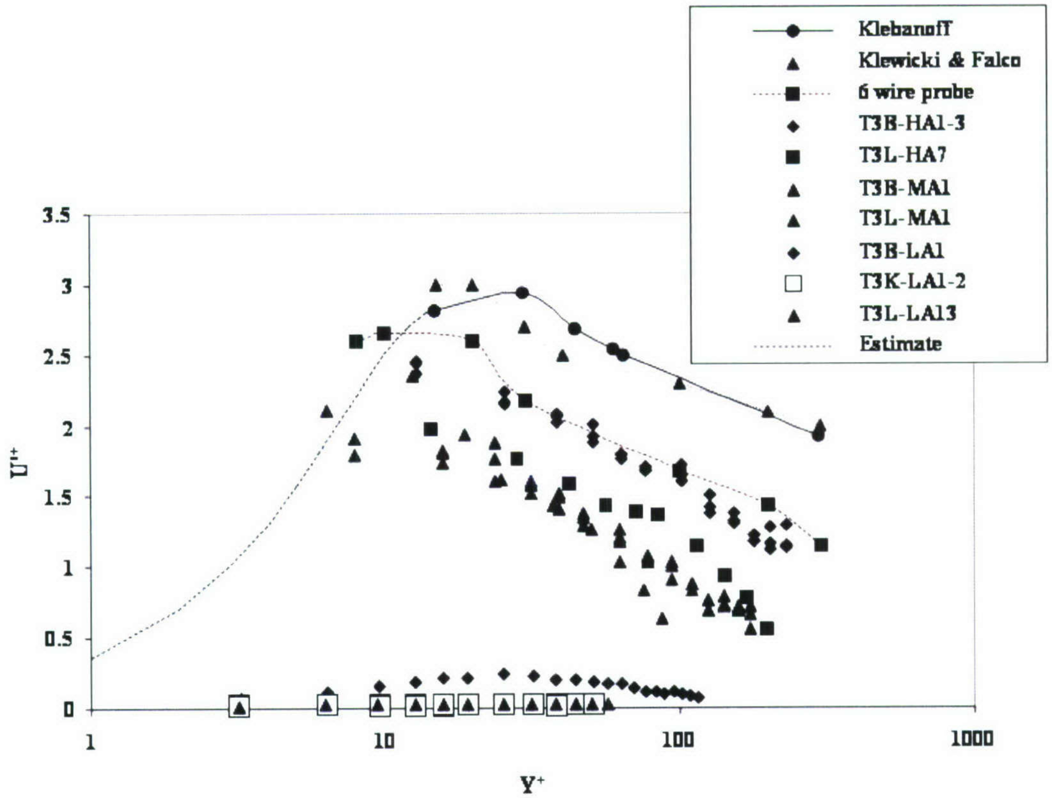


Figure 66. Effect of Velocity on Turbulence Intensity

8.6 Effect of Differences between Measured and Operational Velocity Profiles

The analysis provides a quantitative comparison of how well the velocity profiles measured in the 5-cm Wind Tunnel agree with the specified operational values. At the high and mid velocity conditions, corresponding to the operational profiles at 6 and 3 m/s, respectively, the friction velocities are 0.180, 0.096 m/s with an average intercept C of 6.6 which are different from the Operational values of 0.1966, 0.1038 m/s and C of 5.5. Thus, the experimental friction velocity data are consistently lower by 7.5 and 8.4%, respectively than specified by the reference and the intercept is consistently higher by 18%.

A more meaningful criterion to quantify this comparison is to relate it to its subsequent effect on the agent evaporation rate which represents the ultimate purpose of the 5-cm Wind Tunnel. A two-dimensional model was formulated based on a Couette flow that showed that the characteristic convection velocity is the friction velocity. The effect of differences between the experimental and operational velocity profiles can be compared in terms of how well their respective friction velocities agree. The slope of the turbulent semi-logarithmic profile is used to determine the experimental friction velocities from the measurements. The uncertainties in individual tests in terms of two standard deviations in the friction velocity vary considerably with a high of 23% and a low of 4% with an overall average of 8.7%. Thus the potential uncertainty is of the same order as the deficit in the friction velocity with respect to the operational profile. The evaporation model modified by initial test data predicts the evaporation

rate to depend on the friction velocity to the 1/2 power and thus the uncertainty in rate due to friction velocity could be of the order of 4-5%, on average.

The intercept in the Log-Law varies considerably in individual tests from a high of just over 10 to a low in the 4's with an average of 6.6. In principle, the intercept is not relevant to the sub layer velocity gradient and friction velocity. However it is of concern in that it is an indication of the extent of the sub layer and the rapidity of the damping of the turbulence as the wall is approached. In addition, it may be an indication of the lack of two-dimensionality of the flow.

The low velocity condition is a special case. Theoretically the operational profile predicts that most of the low speed data to be mostly in the buffer layer and that the semi-logarithmic slope cannot be used to determine the fiction velocity. As an alternative, the data were extrapolated to the wall and the slope of the resulting curve used to determine the shear stress and friction velocity. The results show the friction velocity to be 0.04 m/s compared to the expected value of 0.02 m/s. The data plotted in law of the wall coordinates show that the experimental data deviate significantly from that of a turbulent profile, suggesting the low speed measurements were essential laminar. Examination of the turbulent intensity data confirm that the velocity fluctuation level is substantially lower than observed for the other velocities. It is probably impossible to produce a turbulent boundary layer at such a low velocity in a 5-cm tunnel. The friction velocity of the laminar flow can also be related to a hypothetical 2 m turbulent boundary layer at a velocity of about 1 m/s.

9. CONCLUSIONS

1. A special 5-cm Wind Tunnel was designed specifically to measure the release and retention of Chemical Warfare Agents (CWAs) from various materials under constant, simulated environmental conditions. These wind tunnels and associated instrumentation provide a new capability for measurement of the environmental fate of any toxic chemical contaminant on most surfaces.

2. A wind tunnel was successfully designed that meets the requirements for a reproducible and uniform flow field around contaminant drops on a surface and the tunnel can be fitted within the dimensions of a standard chemical fume hood that meets safety requirements for CWA operations.

3. The tunnel can create vertical velocity profiles that match the lower portion of a wind induced atmospheric boundary layer.

4. The specified velocity profiles are uniform across the area containing the droplet(s) on surface materials, within the wind tunnel test section.

5. The specified velocity profiles can be characterized by a single reference velocity at a specified height in the test section and this reference velocity can then be employed during each experiment to set and then continuously monitor the wind speed.

6. Free stream turbulence in the 5-cm Wind Tunnel has similar values to those of a typical atmospheric boundary layer.

7. The wind speed profile measurements and fit to the operational profile are closely matched and reproducible; therefore, the hot wire measurements during a wind tunnel experiment can be related to a wind speed measured at a 2-m height or other height at a weather station at an airfield or other Fixed Site. The 2-m height wind speed data can then be continuously input into a real time model during a chemical attack and the volatilization rate can be estimated from the 5-cm Wind Tunnel data in which the wind speed was monitored at 10 mm, or any similar reference height.

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APPENDIX I - HOT WIRE ANEMOMETER CALIBRATION PROCEDURE

The calibration of a single component hot wire anemometer is relatively straight forward. Typically better sensitivity can be achieved if the calibration is limited to the range of velocities expected in the experiments. For the 5-cm Wind Tunnel this wind speed range was selected to be approximately 0.05 to 10-m/s. Knowing the calibration wind speed range, the atmospheric pressure and room air temperature, a calibration spreadsheet was generated that provided the different tunnel configurations and pressures required to achieve each wind speed. The calibration spread sheet is shown in Table AI.1.

Table AI-1. Hot Wire Anemometer Calibration Spreadsheet

Atm Press	757	mm-hg	Enter Atm Press and Temp on "No Plate Sheet"
Atm Temp	26.1	deg C	
K	1.021023		Standard Conditions 29.92 in-Hg (760 mm-Hg) and 70 deg F

	Velocity (m/s)	Plate #2				Plate #1		No Plate		
		(in-H2O)	0.1" WG (%FS)	0.5" WG (%FS)	5.0" WG (%FS)	(in-H2O)	5.0" WG (%FS)	(in-H2O)	0.5" WG (%FS)	5.0" WG (%FS)
1	0.05	0.0056	5.6							
2	0.08	0.0130	13.0							
3	0.11	0.0301	30.1							
4	0.17	0.0694	69.4							
5	0.25	0.1602		32.0						
6	0.38	0.3698		74.0						
7	0.57	0.8536			17.1					
8	0.85	1.9705			39.4					
9	1.28	4.5490			91.0					
10	1.92					0.263	5.3			
11	2.88					0.597	11.9			
12	4.32					1.355	27.1			
13	6.49					3.079	61.6			
14	9.73							0.223	44.6	
15	14.60							0.500		10.0
16	21.89							1.121		22.4
17	32.84							2.514		50.3
18	45.00							4.708		94.2

Using the atmospheric pressure and room temperature as input, a correction factor K is calculated to determine the true air density for non-standard conditions. The spreadsheet is used to compute the difference between the test section and settling chamber pressures which is then used, in combination with the appropriate orifice plate and electronic pressure gage required, to achieve the desired calibration velocity. Once these setting have been established, the calibration can be performed.

Another important aspect of hot wire anemometry that should be noted is the effect of different air temperatures on the resulting measurements. Because hot wire/film anemometry relies on the principles of heat transfer, a difference between the calibration air temperature and the air temperature of the actual experiments can introduce an error of

approximately 1% per °C of difference. The test matrix temperatures for the Agent Fate program consisted of three constant values (15, 35 and 50 °C). Because of the calibration instrumentation available, a room temperature of 23-25 °C was the typical calibration temperature. Thus, an ambient air temperature difference occurred between the calibration and velocity profile measurements which required a correction to be performed on the resulting measurements.

An analytical correction is the most popular and widely used temperature compensation technique and relies on the principles of heat transfer and requires a combined measurement of both the fluid's velocity (i.e., voltage difference) and temperature. Before the output voltage is converted to a velocity, the following expression is applied to correct for the temperature difference.

$$E_{corrected} = E_{out}\,[(T_s - T_{test})/(T_s - T_{cal})]^{1/2}$$

Where:

$E_{corrected}$ = corrected bridge output
T_s = hot wire/film sensor temperature (typically 250 °C)
T_{cal} = calibration temperature (23 to 25 °C for this study)
T_{test} = air temperature during the test
E_{out} = uncorrected bridge output voltage from the anemometer system.

TSI indicates that this correction is valid over temperature differences of approximately 50 °C.

1. Turn on IFA300, data acquisition PC and start ThermalPro® software, select Calibration/Probe Data from the toolbar, see Figure 5.

2. Connect appropriate length co-axial cable and probe holder to desired input channel on the IFA300 mainframe.

3. Install the IFA300 thermocouple in a suitable location to measure the tunnel air temperature. This temperature will become the calibration temperature.

4. Install a shorting probe into probe holder and press the "Read" button on the Calibration/Probe Data window, see Figure A.1. This will read the cable and probe holder resistance.

5. Fill in the additional information from the selected hot wire/film storage box, such as sensor serial number, sensor type, wire or film and operating resistance. See the TSI IFA300 operator's manual for a discussion on setting the offset and gain. For fluid temperature reading select the appropriate channel that the thermocouple is plugged in to on the back of the IFA300, usually channel A. The calibration method is typically "Acquire E and Type Velocity" in a manual mode. Thus the IFA300 will automatically read the output voltage, and the operator must type in the velocity for each calibration data point. Once the probe data sheet is filled in,

press the green "Calibrate" button, which will display the "Calibration Conditions Setup" window, see Figure A.2.

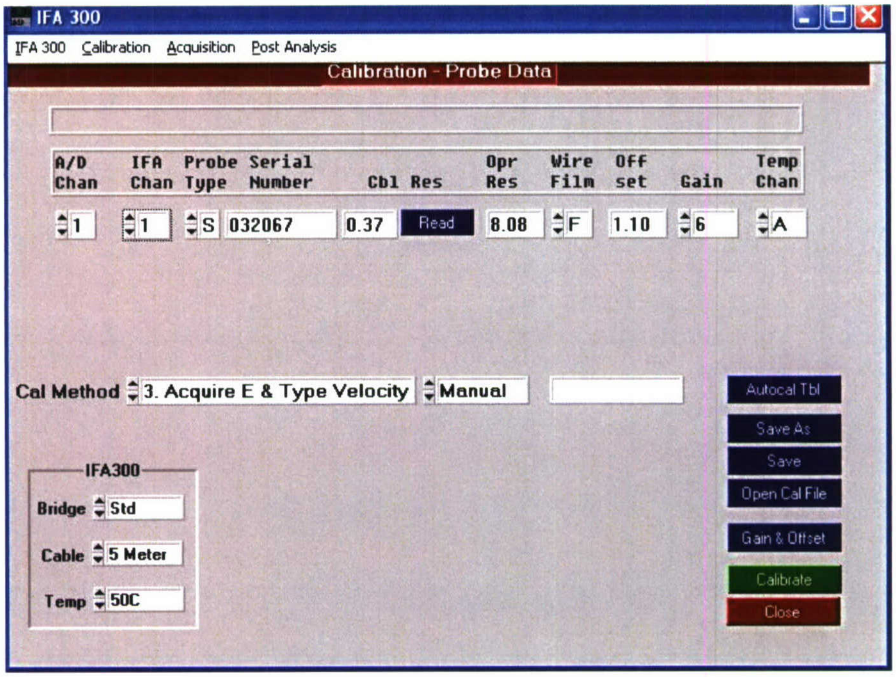

Figure AI-1. ThermalPro® software, Calibration/Probe Data Window

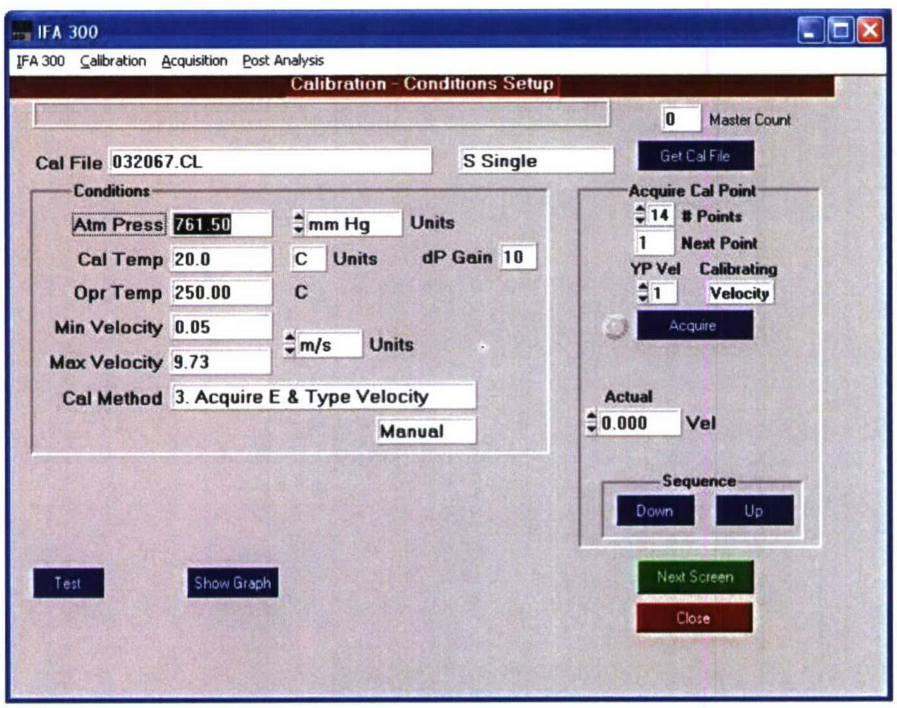

Figure AI-2. ThermalPro® software, Calibration Conditions Setup Window

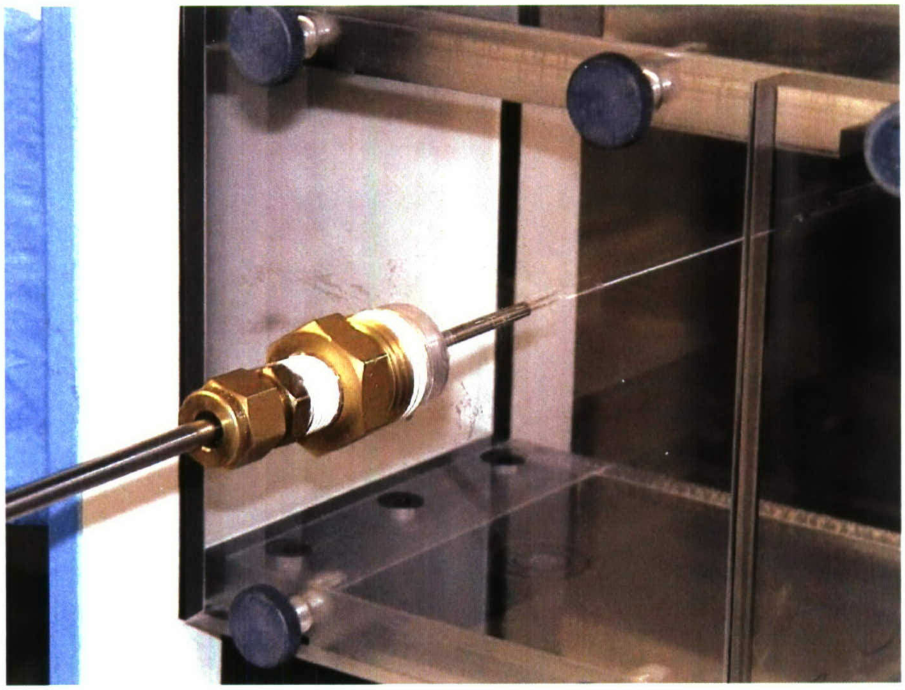

Figure AI-3. Hot Wire/film Installed in TSI Calibration Wind Tunnel

6. Replace the shorting probe with the hot wire/film sensor to be calibrated and install the probe holder and sensor into the TSI Calibration Wind Tunnel. Align the sensor in the center of the test section in the proper orientation to the flow, as shown in Figure A.3.

7. Fill in the additional information needed on the "Calibration Conditions Setup" window such as atmospheric pressure, tunnel air temperature and the anticipated min and max velocity range for which the calibration will cover, taking care to select the correct units

8. Referencing the Hotfilm Calibration Spreadsheet (Table 2 in main text) configure the tunnel and pressure reading equipment for the first velocity, switch power onto the tunnel and set the first pressure/velocity.

9. Manually input the velocity from the spreadsheet into the "Calibration Conditions Setup" window and press the "Acquire" button. The indicator next to this button will turn read while the voltage is being read.

10. Repeat steps 8 and 9 for each velocity in the spreadsheet. When finished press the green "Next Screen" button and the acquired data will be displayed in tabulated form.

11. Pressing the "Curve" button displays a graph of the calibration data, a 4^{th} order polynomial fit of the data, and the % error between the data and the curve fit. An example of curve is shown in Figure A.4.

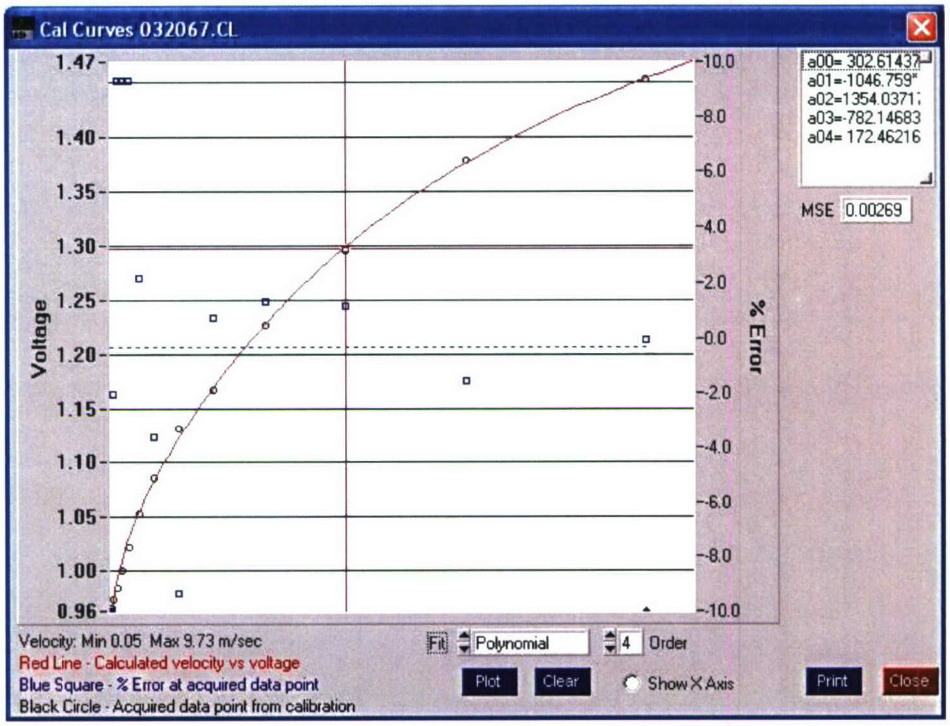

Fig AI-4. Hot Wire/Film Calibration Plot

Once calibrated the hot wire anemometer is available for use in experiments. A drawback to the research grade hot wire/film sensors is that they require extreme care in use. They are easily damaged and/or broke. If this occurs then a new sensor has to be acquired and the calibration process repeated. For this reason, it usually makes good sense to calibrate several sensors so that they are available in case one is broken, and thus testing is not interrupted.

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APPENDIX II

VELOCITY CHARACTERIZATION PROCEDURE

A set procedure was followed in measuring the velocity profiles. The first step was to securely install the wind tunnel to be characterized onto the laboratory workbench to reduce any motion between the tunnel and the height gage (24-in Mitutoyo Series 192) used to position the hot wire anemometer above the tunnel floor. The height gage was positioned over the desired position.

Determining the reference height of the hot wire anemometer was an extremely crucial step in the measurement process for two reasons. First, it provided an accurate position of the probe above the wind tunnel floor so that height vs. velocity correlations could be made. Second, it provided protection from inadvertently damaging the probe by running it into the floor. To accomplish this zeroing of the height gage, an old broken probe was modified with a flat machined tip. The difference in length from this machined probe and the actual probe to be used for measurements was determined by using an optical comparator. This device enlarges small objects and permits measurements to within 25 μm. The selection of common reference points on each probe body allowed the difference in their lengths to be determined. The machine probe was placed in the probe holder on the height gage and the height gage was lowered until the machined probe just touched the piston on the tunnel floor. At this point the height gage was zeroed and the process of raising and lowering the machined probe was repeated to verify that a reproducible zero has been obtained. Once satisfied that the zero height was reproducible, the height gage was raised to the length difference between the machined and actual probe determined from the optical comparator. This height was now the true zero height for the actual probe and the height gage is once again zeroed at this position. Finally the height gage was raised and the machined probe removed.

Air conditioned to the required temperature and humidity was routed from the Miller-Nelson ECU system to the tunnel inlet. At the same time, heating tape surrounding the tunnel was turned on and the tunnel allowed to equilibrate to the appropriate test conditions. This often required several hours to achieve. When this was accomplished, the associated measuring instrumentations and computers are turned on and allowed to warm up including the ThermalPro® system. From the latter's menu bar "Acquisition" and "Probe Table" was selected. The associated computer monitor screen shown in Figure AII.1 was displayed. After verifying that the correct sensor is displayed in the probe table, the cable and probe resistance were measured by installing the shorting plug in the probe holder and pressing the "Read Cable" button. Once read, the software prompted replacement of the shorting plug with the appropriate sensor. Then the "Read Probe" button was pressed and the probe resistance read. After verifying that the other settings listed are correct and any values changed, the "SaveLine" button was pressed and the Probe Table was updated with the current values. Finally the "Rename" button in the experiment area of the screen was pressed and a file name entered for the data files saved during the experiment. When this was completed, the "Next Screen" button was pressed to proceed to the "Acquisition Conditions Setup" screen as shown in Figure II.2.

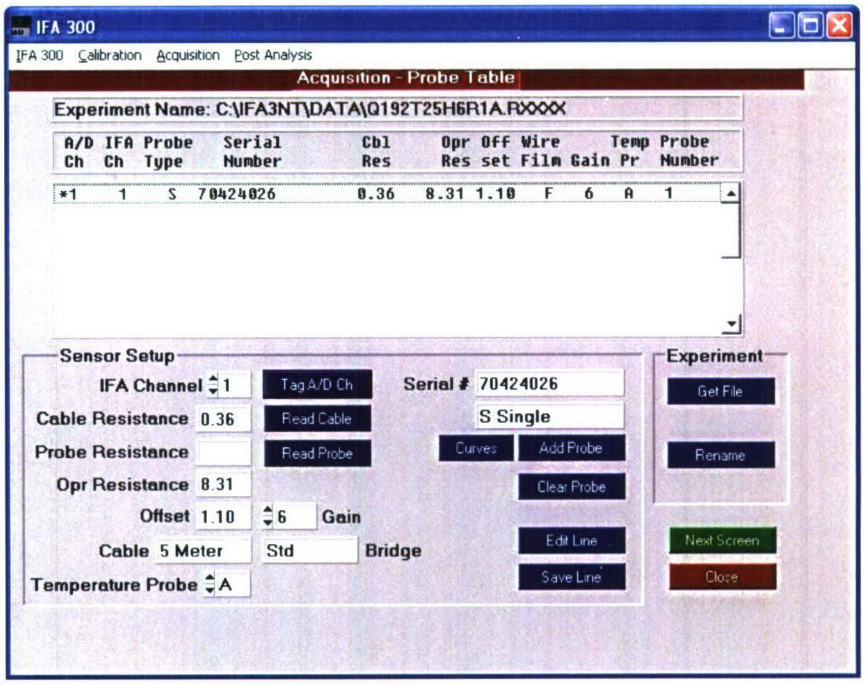

Figure AII-1. TSI ThermalPro® Software; Acquisition - Probe Table Screen

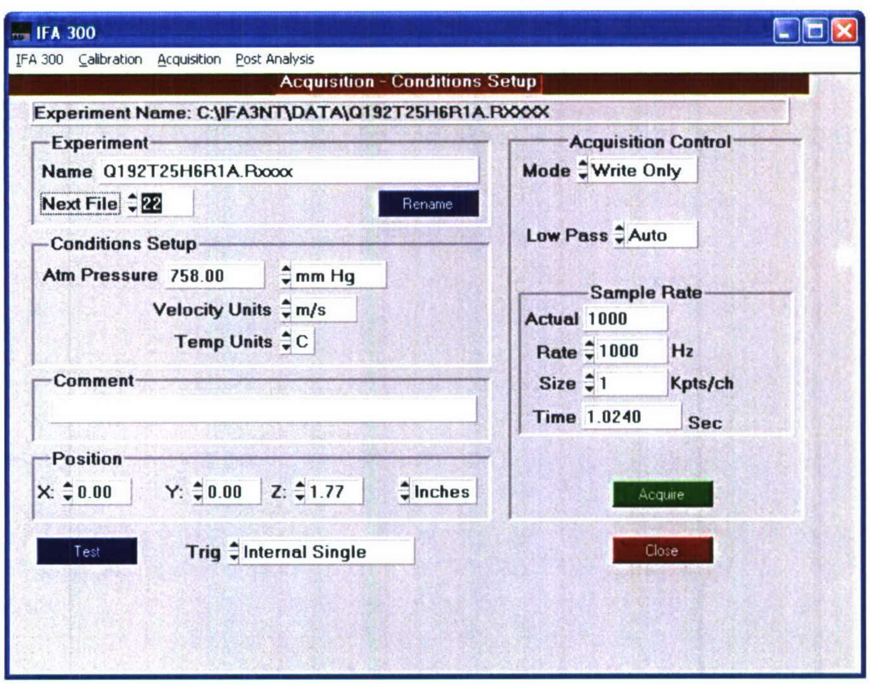

Figure AII-2. TSI ThermalPro® Software, Acquisition Conditions Setup Screen

The "Acquisition Conditions Setup" screen listed the settings that were to be used for acquiring the velocity profiles. The data on the left side of this screen was updated as required. The "Acquisition Control" area on the right side of the screen determined how much and how fast the velocity readings were to be taken. Typically, 1,000 readings over a 1 second time interval was found to be adequate.

At this point in the test setup, the hot wire sensor was installed in the probe holder. The sensor was lowered into the tunnel and the flexible rubber seal (see Figure 26) placed between the sensor and the test section ceiling. This seal prevented air from entering or exiting the tunnel through the instrument port that might otherwise have influenced the velocity profile measurements. The sensor was positioned at 0.5 cm above the wind tunnel floor and the final flow adjustments were made prior to measuring the profile. The "Acquisition Control Mode" was set to "View Only" and the air velocity was monitored. The tunnel flow rate was adjusted until the velocity was equal to the operational value at the 0.5-cm height for the selected velocity condition (low, medium or high). Once the correct velocity at 0.5 cm had been established, the various parameters such as Miller-Nelson settings, flow meter settings, tunnel humidity, temperature and static pressure were recorded.

The "Acquisition Control Mode" was then switched back to "Write Only" and the hot wire sensor lowered to the lowest measurement height of 1.27mm above the test section floor. Although it was desirable to go closer to the surface, this limiting height was selected to avoid a heat convection phenomenon that affected the hot wire output below this height as well as to prevent inadvertent damage to the sensors if it came in contact with the tunnel floor. A profile reading was obtained at each of the 21 probe heights covering a range of 0.127 to 4.5 cm. The complete listing of probe heights is shown in Table II.1.

Table AII-1. Probe Heights for 5-cm Wind Tunnel Characterization

Probe Height (y)	
(in)	(cm)
0.050	0.127
0.098	0.25
0.148	0.376
0.197	0.5
0.246	0.625
0.295	0.75
0.394	1
0.492	1.25
0.591	1.5
0.689	1.75

Probe Height (y)	
0.787	2
0.886	2.25
0.984	2.5
1.083	2.75
1.181	3
1.280	3.25
1.378	3.5
1.476	3.75
1.575	4
1.673	4.25
1.772	4.5

After the IFA300 recorded a measurement, the probe was raised to the next height. This was repeated until the last height of 4.5 cm. At this point the measurement process was over and the stored readings were analyzed by the ThermalPro® software. This involved a number of statistical calculations. However, the two most critical results were the average total velocity and the turbulence intensity. The final step was to build the velocity field, in which all of the readings, which up to this point have been stored in a number of separate files, were

combined into tabulated and plotted formats. Typically, the ThermalPro® plots were not used and the tabulated data was imported into Microsoft Excel® for comparison plotting with other profiles. Normally, two plots were made at each position and wind speed setting. The hot wire anemometer was then repositioned to the 0.5-cm height and the process repeated.

Care must be taken in interpreting the hot wire velocity measurements as the probe approaches the floor. Heat transfer effects due to the proximity of the metal floor wall can affect the temperature of the hot wire giving false velocity readings. The closest measurement to the test section floor for the 5-cm Wind Tunnel characterization was 0.050 in. (1.27 mm).

APPENDIX III

TABULATED VELOCITY PROFILES

LIST OF FIGURES

	Operational Velocity		
Probe Height	Low	Medium	High
(cm)	m/s	m/s	m/s
0.010	0.003	0.074	0.265
0.016	0.004	0.121	0.434
0.027	0.007	0.198	0.713
0.044	0.012	0.326	1.146
0.072	0.020	0.534	1.609
0.119	0.033	0.778	2.071
0.195	0.053	1.022	2.533
0.320	0.173	1.325	2.825
0.500	0.194	1.431	3.026
0.525	0.196	1.446	3.054
0.862	0.218	1.557	3.264
1.000	0.222	1.580	3.308
1.414	0.236	1.649	3.439
2.321	0.253	1.740	3.611

Figure AIII-1. 5-cm Tunnel Operational Profiles

		Tunnel 3A				**Tunnel 3A**			
		Position A				Position A			
		Q11T35H50R1		Q11T35H50R2		Q130T35H50R1		Q130T35H50R2	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.131	2.831	0.133	2.936	0.908	19.044	0.905	17.964
0.098	0.25	0.146	4.025	0.145	4.557	1.218	14.874	1.174	16.425
0.148	0.376	0.169	4.418	0.165	5.693	1.308	15.050	1.295	14.667
0.197	0.5	0.188	4.258	0.183	5.215	1.416	13.059	1.364	12.692
0.246	0.625	0.203	4.704	0.200	5.667	1.471	10.688	1.433	11.523
0.295	0.75	0.213	4.913	0.212	5.887	1.526	10.514	1.469	9.705
0.394	1	0.222	5.022	0.220	6.142	1.582	8.947	1.546	8.023
0.492	1.25	0.220	5.249	0.220	5.736	1.679	7.322	1.637	6.934
0.591	1.5	0.210	4.731	0.209	6.184	1.738	5.773	1.651	5.684
0.689	1.75	0.200	4.527	0.197	5.624	1.732	5.307	1.713	5.418
0.787	2	0.187	4.447	0.186	6.213	1.759	5.385	1.726	4.739
0.886	2.25	0.177	5.430	0.174	5.248	1.783	3.613	1.742	4.485
0.984	2.5	0.169	5.068	0.168	5.976	1.782	4.052	1.740	3.505
1.083	2.75	0.162	5.082	0.162	5.339	1.765	3.954	1.729	3.556
1.181	3	0.157	5.005	0.160	5.097	1.765	3.330	1.738	3.612
1.280	3.25	0.153	5.640	0.154	4.860	1.735	3.312	1.720	4.069
1.378	3.5	0.150	4.992	0.150	4.737	1.756	3.602	1.690	3.901
1.476	3.75	0.147	4.719	0.147	4.177	1.685	5.233	1.672	5.076
1.575	4	0.143	4.822	0.143	4.137	1.619	7.496	1.588	8.012
1.673	4.25	0.137	4.174	0.137	3.577	1.473	10.778	1.444	10.435
1.772	4.5	0.123	3.029	0.127	3.622	1.179	15.033	1.140	16.770

Figure AIII-2. Tunnel 3A (Low and Medium Velocities)

		Tunnel 3B				Tunnel 3B				Tunnel 3B			
		Position A				Position C				Position B			
		Q12T35H50R2		Q12T35H50R6		Q12T35H50R1		Q12T35H50R2		Q12T35H50R1		Q12T35H50R2	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.128	2.152	0.126	2.945	0.129	2.195	0.131	2.522	0.150	1.268	0.149	1.703
0.098	0.25	0.142	3.261	0.139	4.246	0.137	3.195	0.136	3.316	0.148	2.220	0.149	2.696
0.148	0.376	0.163	3.662	0.161	4.408	0.154	4.287	0.153	4.169	0.160	3.044	0.160	3.286
0.197	0.5	0.183	3.981	0.179	5.496	0.170	4.501	0.170	4.616	0.173	3.348	0.177	4.035
0.246	0.625	0.197	4.340	0.197	5.420	0.187	5.106	0.188	4.883	0.191	3.955	0.190	4.687
0.295	0.75	0.208	4.144	0.207	5.795	0.205	4.351	0.201	5.478	0.205	3.955	0.204	5.078
0.394	1	0.222	4.280	0.220	5.683	0.218	3.871	0.222	4.950	0.225	4.034	0.230	4.834
0.492	1.25	0.217	4.297	0.218	5.174	0.225	4.194	0.228	4.929	0.238	4.014	0.239	4.901
0.591	1.5	0.210	3.888	0.205	5.705	0.224	4.145	0.221	5.439	0.240	4.040	0.238	4.403
0.689	1.75	0.194	4.202	0.194	5.729	0.217	4.614	0.216	4.698	0.228	3.592	0.228	4.291
0.787	2	0.179	3.971	0.181	6.121	0.206	4.802	0.207	5.631	0.218	3.934	0.216	4.981
0.886	2.25	0.166	4.053	0.170	5.472	0.198	4.375	0.196	4.637	0.206	4.497	0.204	4.242
0.984	2.5	0.156	4.314	0.161	5.633	0.186	4.438	0.183	4.725	0.192	4.417	0.194	4.318
1.083	2.75	0.147	3.975	0.153	5.255	0.175	4.462	0.174	4.511	0.186	4.099	0.186	4.690
1.181	3	0.140	3.401	0.147	4.515	0.171	4.716	0.167	4.069	0.181	4.113	0.183	4.213
1.280	3.25	0.136	3.327	0.143	4.474	0.164	4.656	0.161	4.525	0.177	4.259	0.178	3.702
1.378	3.5	0.132	3.046	0.140	4.161	0.160	4.631	0.158	4.300	0.175	4.311	0.176	4.170
1.476	3.75	0.130	3.478	0.137	3.947	0.155	4.823	0.152	4.150	0.174	4.097	0.174	3.411
1.575	4	0.131	2.944	0.139	4.007	0.150	3.897	0.149	3.666	0.171	3.998	0.171	3.636
1.673	4.25	0.130	2.714	0.139	3.682	0.146	4.042	0.143	3.855	0.166	3.688	0.166	3.239
1.772	4.5	0.124	2.495	0.133	3.209	0.137	2.930	0.136	2.788	0.155	2.589	0.156	2.847

Figure AIII-3. Tunnel 3B (Low Velocity)

		Tunnel 3B				Tunnel 3B			
		Position D				Position E			
		Q12T35H50R1		Q12T35H50R2					
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.150	3.311	0.151	3.055	0.135	2.629	0.146	2.660
0.098	0.25	0.167	4.506	0.167	4.660	0.144	4.834	0.154	4.348
0.148	0.376	0.191	5.516	0.190	6.035	0.165	5.047	0.171	5.123
0.197	0.5	0.207	5.624	0.207	5.953	0.184	5.641	0.186	5.519
0.246	0.625	0.227	6.214	0.224	6.364	0.199	5.177	0.205	5.869
0.295	0.75	0.238	6.006	0.236	6.438	0.215	5.945	0.218	5.997
0.394	1	0.243	5.302	0.245	6.188	0.228	5.511	0.235	7.025
0.492	1.25	0.237	5.192	0.238	6.372	0.241	5.431	0.242	6.433
0.591	1.5	0.221	5.271	0.222	6.815	0.237	4.848	0.237	6.929
0.689	1.75	0.203	4.573	0.204	6.988	0.225	5.344	0.225	5.930
0.787	2	0.188	6.061	0.188	6.050	0.214	5.507	0.216	6.324
0.886	2.25	0.174	5.469	0.174	5.890	0.202	5.537	0.204	6.124
0.984	2.5	0.164	5.994	0.163	5.982	0.194	5.098	0.197	4.850
1.083	2.75	0.155	5.780	0.155	5.678	0.187	5.980	0.189	4.766
1.181	3	0.149	5.633	0.149	5.114	0.181	5.607	0.182	4.597
1.280	3.25	0.145	4.964	0.144	4.798	0.176	5.149	0.176	4.442
1.378	3.5	0.143	5.575	0.143	4.599	0.172	5.426	0.172	4.797
1.476	3.75	0.144	5.218	0.143	4.175	0.168	5.505	0.170	5.014
1.575	4	0.144	5.277	0.144	4.361	0.167	5.773	0.168	4.919
1.673	4.25	0.147	4.516	0.146	4.160	0.164	4.842	0.167	4.281
1.772	4.5	0.143	3.561	0.143	3.760	0.156	3.990	0.158	3.730

Figure AIII-3. (Continued). Tunnel 3B (Low Velocity)

Probe Height		Tunnel 3B				Tunnel 3B				Tunnel 3B			
		Position A				Position C				Position B			
		Q143T35H50R2		Q143T35H50R3		Q143T35H50R1		Q143T35H50R2		Q143T35H50R1		Q143T35H50R2	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.05	0.127	1.029	17.242	0.975	18.277	0.962	17.594	0.907	18.866	0.822	18.113	0.839	17.497
0.098	0.25	1.266	14.154	1.267	14.201	1.193	15.543	1.164	14.917	1.123	16.431	1.060	16.829
0.148	0.376	1.402	11.306	1.342	12.412	1.322	13.042	1.315	13.079	1.266	14.419	1.252	15.784
0.197	0.5	1.441	10.915	1.458	10.422	1.406	10.609	1.361	11.817	1.342	11.383	1.336	13.479
0.246	0.625	1.495	10.055	1.496	9.251	1.419	10.655	1.436	10.824	1.424	10.590	1.394	10.335
0.295	0.75	1.562	8.519	1.535	8.149	1.509	8.538	1.485	9.620	1.439	9.815	1.450	9.394
0.394	1	1.606	7.378	1.583	7.219	1.546	9.144	1.547	8.569	1.480	8.952	1.528	8.275
0.492	1.25	1.640	6.242	1.650	6.442	1.616	7.669	1.566	7.373	1.512	7.779	1.508	8.397
0.591	1.5	1.668	5.329	1.666	5.960	1.621	7.648	1.611	7.526	1.536	8.927	1.490	9.007
0.689	1.75	1.724	5.035	1.701	4.989	1.662	7.216	1.597	7.834	1.471	11.129	1.512	9.424
0.787	2	1.711	4.398	1.702	4.395	1.618	8.032	1.632	6.855	1.509	10.087	1.449	10.517
0.886	2.25	1.724	4.558	1.718	4.157	1.661	7.322	1.646	6.808	1.484	9.927	1.464	9.637
0.984	2.5	1.714	3.979	1.714	4.061	1.668	7.134	1.647	6.763	1.491	10.800	1.459	11.614
1.083	2.75	1.724	3.812	1.738	3.224	1.644	7.513	1.655	6.216	1.520	9.353	1.505	11.689
1.181	3	1.724	3.344	1.708	3.861	1.649	6.108	1.646	6.067	1.598	8.711	1.537	9.661
1.280	3.25	1.709	3.774	1.702	3.611	1.619	6.240	1.643	6.205	1.585	7.909	1.599	7.886
1.378	3.5	1.687	4.119	1.692	3.873	1.627	6.811	1.646	6.725	1.594	7.310	1.601	8.069
1.476	3.75	1.685	5.168	1.643	4.845	1.625	7.021	1.600	6.851	1.594	6.896	1.598	6.497
1.575	4	1.613	6.657	1.605	7.041	1.518	7.177	1.537	7.597	1.544	8.043	1.510	9.138
1.673	4.25	1.478	10.654	1.495	10.200	1.410	11.829	1.420	9.673	1.340	12.156	1.399	12.580
1.772	4.5	1.227	16.871	1.201	16.420	1.169	17.303	1.131	16.323	1.129	19.241	1.084	19.912

Figure AIII-3. (Continued). Tunnel 3B (Medium Velocity)

Probe Height		Tunnel 3B				Tunnel 3B			
		Position D				Position E			
		Q143T35H50R1		Q143T35H50R2		Q143T35H50R1		Q143T35H50R2	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.05	0.127	1.004	17.465	0.988	16.788	0.995	17.747	1.009	17.122
0.098	0.25	1.227	15.138	1.250	14.095	1.262	13.033	1.221	14.798
0.148	0.376	1.365	12.311	1.402	12.096	1.387	12.199	1.355	13.429
0.197	0.5	1.424	10.332	1.450	10.489	1.461	10.038	1.455	9.516
0.246	0.625	1.502	10.263	1.523	9.055	1.484	9.253	1.487	9.305
0.295	0.75	1.514	8.543	1.542	8.666	1.537	8.690	1.509	9.109
0.394	1	1.597	7.166	1.618	7.576	1.606	6.534	1.596	7.282
0.492	1.25	1.625	7.223	1.647	7.021	1.662	6.136	1.652	6.382
0.591	1.5	1.670	6.018	1.694	5.669	1.686	5.551	1.667	5.600
0.689	1.75	1.711	4.674	1.728	4.867	1.678	4.971	1.707	4.625
0.787	2	1.705	4.378	1.714	4.355	1.721	4.489	1.706	4.496
0.886	2.25	1.707	3.864	1.733	4.807	1.717	3.917	1.715	4.068
0.984	2.5	1.714	4.253	1.736	4.240	1.726	3.820	1.716	4.151
1.083	2.75	1.743	3.946	1.734	3.939	1.725	3.652	1.714	3.759
1.181	3	1.738	3.553	1.729	4.239	1.708	3.526	1.706	3.769
1.280	3.25	1.737	4.034	1.714	3.979	1.712	3.510	1.695	3.659
1.378	3.5	1.706	3.971	1.702	4.122	1.701	3.884	1.692	4.038
1.476	3.75	1.673	5.209	1.689	4.331	1.648	5.424	1.668	4.913
1.575	4	1.615	6.129	1.621	7.004	1.598	7.184	1.574	7.122
1.673	4.25	1.490	10.307	1.529	8.424	1.491	8.849	1.469	9.819
1.772	4.5	1.256	14.603	1.277	15.506	1.243	15.536	1.203	17.004

Figure AIII-3. (Continued). Tunnel 3B (Medium Velocity Continued)

		Tunnel 3B				Tunnel 3B				Tunnel 3B			
		Position A				Position C				Position B			
		Q309T35H50R1		Q365T35H50R2		Q309T35H50R1		Q309T35H50R2		Q309T35H50R1		Q365T35H50R2	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	2.400	16.350	2.423	15.745	2.051	18.016	2.045	17.770	1.940	18.181	1.992	18.602
0.098	0.25	2.735	12.603	2.819	12.527	2.473	14.095	2.359	15.200	2.290	14.751	2.338	14.952
0.148	0.376	3.009	10.944	2.954	10.727	2.529	12.297	2.597	12.149	2.498	12.171	2.467	12.115
0.197	0.5	3.100	9.638	3.097	10.347	2.688	10.754	2.650	11.706	2.654	10.426	2.622	11.265
0.246	0.625	3.142	9.119	3.174	8.944	2.750	9.857	2.772	9.854	2.734	9.320	2.756	9.636
0.295	0.75	3.177	8.505	3.233	8.416	2.831	9.486	2.811	10.005	2.757	8.971	2.761	8.457
0.394	1	3.410	8.051	3.462	7.515	3.096	8.651	3.030	8.754	2.850	8.924	2.923	8.146
0.492	1.25	3.475	6.547	3.499	6.325	3.111	8.222	3.155	8.363	2.821	8.843	2.913	8.666
0.591	1.5	3.504	5.937	3.620	5.983	3.225	8.262	3.238	7.497	2.858	8.874	2.868	9.494
0.689	1.75	3.514	5.517	3.566	5.362	3.184	7.207	3.220	7.917	2.794	10.528	2.791	10.772
0.787	2	3.723	4.979	3.624	5.471	3.281	8.399	3.348	7.715	2.683	10.611	2.790	10.705
0.886	2.25	3.732	5.543	3.591	4.929	3.292	7.962	3.244	7.431	2.755	10.337	2.819	10.402
0.984	2.5	3.676	5.230	3.597	4.606	3.338	7.726	3.307	6.842	2.821	10.899	2.788	10.447
1.083	2.75	3.673	4.474	3.652	4.900	3.362	7.889	3.181	7.933	2.932	10.851	2.907	9.383
1.181	3	3.689	4.401	3.680	5.533	3.356	6.667	3.242	7.534	3.048	9.283	3.023	9.682
1.280	3.25	3.627	4.150	3.616	4.531	3.245	7.291	3.240	6.909	3.149	8.227	3.043	8.506
1.378	3.5	3.691	4.490	3.653	4.173	3.221	7.230	3.174	7.800	3.121	7.355	3.179	6.556
1.476	3.75	3.593	5.053	3.562	4.833	3.073	7.368	3.100	7.619	3.074	6.975	3.147	6.645
1.575	4	3.433	5.604	3.392	6.281	3.105	7.805	3.087	8.255	2.936	7.542	2.941	8.106
1.673	4.25	3.231	7.997	3.209	8.279	2.860	10.026	2.867	9.965	2.713	10.873	2.734	10.303
1.772	4.5	2.897	12.191	2.835	12.766	2.579	13.813	2.482	13.934	2.219	18.289	2.331	16.798

Figure AIII-3. (Continued). Tunnel 3B (High Velocity)

Probe Height		Tunnel 3B				Tunnel 3B			
		Position D				Position E			
		Q309T35H50R1		Q309T35H50R2		Q309T35H50R1		Q365T35H50R2	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	2.145	17.139	2.174	16.932	2.256	16.091	2.299	15.692
0.098	0.25	2.520	13.017	2.542	14.177	2.632	12.491	2.765	12.462
0.148	0.376	2.701	11.422	2.728	11.041	2.886	10.181	2.905	10.313
0.197	0.5	2.869	9.722	2.899	9.689	2.948	9.760	2.987	9.106
0.246	0.625	2.855	8.829	2.943	9.430	3.081	9.130	2.963	8.648
0.295	0.75	3.006	8.433	3.002	8.381	3.094	7.772	3.191	8.436
0.394	1	3.113	8.828	3.181	7.447	3.260	7.734	3.219	7.000
0.492	1.25	3.289	7.244	3.277	7.274	3.405	6.218	3.328	6.836
0.591	1.5	3.278	6.143	3.288	6.325	3.444	6.195	3.377	6.324
0.689	1.75	3.262	5.764	3.371	5.614	3.404	5.845	3.348	6.125
0.787	2	3.365	6.013	3.395	5.927	3.427	5.612	3.391	5.736
0.886	2.25	3.311	5.652	3.418	6.175	3.471	5.929	3.467	5.944
0.984	2.5	3.283	5.664	3.325	5.847	3.373	5.954	3.533	6.514
1.083	2.75	3.430	5.173	3.409	5.979	3.443	5.486	3.556	5.162
1.181	3	3.379	5.177	3.341	5.264	3.514	5.833	3.486	5.387
1.280	3.25	3.277	4.936	3.370	5.120	3.565	4.764	3.542	4.793
1.378	3.5	3.310	4.569	3.433	4.851	3.442	4.790	3.512	4.550
1.476	3.75	3.351	4.765	3.354	4.518	3.461	4.938	3.436	5.145
1.575	4	3.261	5.585	3.296	6.271	3.294	5.627	3.347	6.441
1.673	4.25	3.038	7.419	3.097	8.281	3.107	8.538	3.128	8.276
1.772	4.5	2.767	11.841	2.767	11.452	2.824	10.967	2.782	11.770

Figure AIII-3. (Continued). Tunnel 3B (High Velocity Continued)

Probe Height		Low Velocity				Medium Velocity				High Velocity			
		Tunnel 3C				Tunnel 3C				Tunnel 3C			
		Position A				Position A				Position A			
		Q12T35H50R1		Q12T35H50R2		Q150T35H50R1		Q150T35H50R2		Q312T35H50R1		Q312T35H50R2	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.122	2.502	0.129	2.587	0.921	18.682	0.924	18.651	2.301	15.952	2.233	15.474
0.098	0.25	0.138	3.374	0.145	3.936	1.179	16.739	1.153	16.191	2.539	13.036	2.465	13.865
0.148	0.376	0.161	4.580	0.167	3.951	1.314	13.505	1.286	13.524	2.784	12.381	2.663	12.509
0.197	0.5	0.183	4.774	0.186	4.269	1.376	12.143	1.378	12.790	2.866	11.773	2.870	11.481
0.246	0.625	0.197	4.976	0.197	4.433	1.427	10.792	1.440	11.158	2.957	10.697	2.985	10.182
0.295	0.75	0.207	4.443	0.211	4.283	1.460	10.312	1.480	9.959	3.081	9.137	3.082	9.609
0.394	1	0.220	4.944	0.221	4.222	1.570	7.893	1.516	9.029	3.304	8.260	3.268	7.729
0.492	1.25	0.218	4.487	0.221	4.306	1.643	7.102	1.657	7.185	3.374	7.463	3.397	7.185
0.591	1.5	0.210	4.280	0.213	4.412	1.692	5.682	1.694	6.396	3.532	6.852	3.454	6.831
0.689	1.75	0.201	4.954	0.200	4.614	1.709	5.201	1.721	5.512	3.628	6.217	3.560	5.935
0.787	2	0.187	4.265	0.187	4.077	1.752	4.328	1.752	4.307	3.758	5.282	3.592	5.623
0.886	2.25	0.174	4.398	0.176	4.802	1.739	4.272	1.761	4.206	3.597	5.002	3.656	4.898
0.984	2.5	0.166	4.899	0.166	4.464	1.750	3.706	1.763	4.044	3.688	4.935	3.655	5.278
1.083	2.75	0.157	4.627	0.159	4.632	1.750	4.005	1.741	3.862	3.649	4.612	3.617	4.539
1.181	3	0.150	3.972	0.153	3.636	1.747	3.914	1.756	3.732	3.703	4.942	3.623	4.960
1.280	3.25	0.145	3.563	0.147	3.246	1.720	3.767	1.748	3.632	3.575	4.604	3.619	5.839
1.378	3.5	0.140	3.284	0.142	3.395	1.705	4.372	1.733	4.135	3.637	4.553	3.612	4.577
1.476	3.75	0.137	3.551	0.137	3.178	1.674	5.306	1.698	5.796	3.536	4.924	3.527	5.571
1.575	4	0.132	3.575	0.133	3.657	1.613	6.464	1.632	6.230	3.348	6.356	3.412	6.311
1.673	4.25	0.127	2.854	0.127	3.078	1.480	10.655	1.507	9.939	3.203	8.548	3.203	8.549
1.772	4.5	0.115	2.121	0.116	2.195	1.190	16.205	1.239	17.141	2.802	13.589	2.905	11.722

Figure AIII-4. Tunnel 3C

Probe Height		Low Velocity				Medium Velocity				High Velocity			
		Tunnel 3D				Tunnel 3D				Tunnel 3D			
		Position A				Position A				Position A			
		Q12T35H50R1		Q12T35H50R2		Q150T35H50R1		Q150T35H50R2		Q312T35H50R1		Q312T35H50R2	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.157	1.163	0.159	1.200	1.001	17.542	0.923	21.010	2.424	15.161	2.380	15.932
0.098	0.25	0.161	2.051	0.163	1.995	1.207	15.742	1.198	15.355	2.668	12.774	2.755	13.039
0.148	0.376	0.174	2.534	0.175	2.524	1.315	13.188	1.338	13.846	2.880	11.321	2.833	11.753
0.197	0.5	0.187	3.127	0.192	3.280	1.378	11.911	1.391	11.743	3.062	9.892	2.981	9.795
0.246	0.625	0.203	3.355	0.200	3.178	1.448	10.410	1.489	10.054	3.119	9.816	3.164	10.062
0.295	0.75	0.211	3.341	0.215	3.483	1.499	9.475	1.475	9.210	3.237	8.903	3.225	9.171
0.394	1	0.231	3.219	0.230	3.727	1.556	8.138	1.552	7.984	3.337	7.832	3.361	7.618
0.492	1.25	0.237	3.308	0.237	3.215	1.603	7.078	1.645	6.664	3.474	7.825	3.430	8.016
0.591	1.5	0.234	3.650	0.234	3.295	1.655	6.159	1.652	6.014	3.561	6.005	3.525	6.208
0.689	1.75	0.228	3.337	0.227	3.557	1.677	5.132	1.680	5.349	3.578	5.531	3.627	5.490
0.787	2	0.217	3.038	0.216	3.417	1.691	5.138	1.724	4.779	3.594	5.425	3.660	5.040
0.886	2.25	0.204	3.185	0.206	2.735	1.700	4.069	1.708	4.383	3.664	4.534	3.677	4.858
0.984	2.5	0.195	2.915	0.196	2.929	1.693	4.308	1.686	4.514	3.643	4.653	3.666	4.764
1.083	2.75	0.187	2.997	0.189	2.845	1.676	3.957	1.705	4.327	3.667	4.433	3.633	4.640
1.181	3	0.181	3.116	0.182	2.502	1.680	4.292	1.700	4.004	3.644	4.498	3.642	4.687
1.280	3.25	0.176	2.730	0.178	2.398	1.693	4.283	1.685	4.087	3.577	4.335	3.645	4.467
1.378	3.5	0.175	2.106	0.175	2.352	1.672	4.600	1.685	4.199	3.597	4.877	3.585	4.741
1.476	3.75	0.172	2.406	0.175	2.687	1.617	5.710	1.627	5.341	3.517	5.576	3.453	5.348
1.575	4	0.171	2.341	0.174	2.188	1.583	6.850	1.580	8.021	3.381	6.700	3.402	6.462
1.673	4.25	0.171	2.048	0.173	2.169	1.496	9.849	1.468	10.716	3.156	8.701	3.271	8.296
1.772	4.5	0.166	1.645	0.168	1.425	1.185	16.106	1.161	16.312	2.840	13.139	2.810	13.007

Figure AIII-5. Tunnel 3D

		Low Velocity				Medium Velocity				High Velocity			
		Tunnel 3E				Tunnel 3E				Tunnel 3E			
		Position A				Position A				Position A			
		Q12T35H50R1A		Q12T35H50R2A		Q148T35H50R1A		Q148T35H50R2A		Q310T35H50R1A		Q310T35H50R2A	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.138	2.143	0.135	2.341	0.940	17.583	0.964	17.883	2.317	17.779	2.272	17.320
0.098	0.25	0.148	3.559	0.147	3.701	1.190	16.070	1.165	16.200	2.698	13.014	2.763	13.046
0.148	0.376	0.171	3.569	0.168	3.595	1.357	12.383	1.337	13.174	2.824	11.375	2.948	10.905
0.197	0.5	0.188	4.732	0.188	5.493	1.420	12.332	1.440	11.424	3.125	9.705	3.049	9.764
0.246	0.625	0.205	4.951	0.203	5.103	1.499	10.248	1.495	10.174	3.082	9.249	3.098	9.295
0.295	0.75	0.216	4.772	0.215	5.211	1.530	9.138	1.539	8.959	3.232	9.176	3.141	8.517
0.394	1	0.234	5.287	0.228	5.127	1.607	8.165	1.602	8.110	3.309	7.939	3.320	7.926
0.492	1.25	0.229	4.982	0.230	4.769	1.681	6.903	1.655	7.030	3.444	7.630	3.398	7.239
0.591	1.5	0.218	5.084	0.217	5.427	1.705	5.364	1.704	6.357	3.596	6.561	3.503	6.802
0.689	1.75	0.206	5.112	0.204	5.444	1.776	5.019	1.761	5.096	3.657	5.625	3.584	5.674
0.787	2	0.194	5.210	0.191	5.622	1.773	4.577	1.781	4.730	3.714	4.989	3.708	5.802
0.886	2.25	0.179	5.077	0.179	5.753	1.813	4.629	1.767	3.871	3.703	4.924	3.821	5.009
0.984	2.5	0.169	5.275	0.170	5.900	1.792	4.079	1.774	3.803	3.764	4.686	3.684	4.474
1.083	2.75	0.162	5.934	0.160	5.594	1.777	3.679	1.774	3.748	3.683	4.674	3.699	5.535
1.181	3	0.155	5.322	0.154	5.804	1.779	3.891	1.779	3.678	3.704	4.105	3.693	4.142
1.280	3.25	0.150	5.491	0.149	5.185	1.756	3.453	1.758	3.836	3.695	4.400	3.650	4.200
1.378	3.5	0.147	4.815	0.145	5.316	1.740	3.498	1.747	3.474	3.635	4.612	3.670	3.849
1.476	3.75	0.145	4.717	0.143	4.849	1.686	4.956	1.701	4.853	3.591	5.343	3.537	5.118
1.575	4	0.143	4.624	0.141	4.849	1.601	7.441	1.612	6.861	3.440	5.965	3.494	5.845
1.673	4.25	0.141	4.042	0.140	4.104	1.512	9.808	1.512	8.866	3.240	8.678	3.221	9.079
1.772	4.5	0.135	3.531	0.134	3.190	1.205	14.343	1.241	16.173	2.947	13.741	2.962	12.629

Figure AIII-6. Tunnel 3E

Probe Height		Tunnel 3F Position A				Tunnel 3F Position B				Tunnel 3F Position C			
		Q16T35H40R1		Q16T35H40R2		Q16T35H40R1		Q16T35H40R2		Q16T35H40R1		Q16T35H40R2	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.137	0.620	0.132	0.598	0.121	0.398	0.123	0.427	0.136	0.535	0.135	0.469
0.098	0.25	0.156	1.040	0.150	0.934	0.129	0.700	0.128	0.718	0.147	0.877	0.146	0.586
0.148	0.376	0.176	1.278	0.171	1.123	0.142	1.071	0.142	1.076	0.164	1.148	0.162	0.948
0.197	0.5	0.194	1.343	0.188	1.267	0.157	1.339	0.155	1.222	0.181	1.432	0.178	1.098
0.246	0.625	0.206	1.347	0.199	1.330	0.171	1.486	0.169	1.334	0.196	1.677	0.192	1.362
0.295	0.75	0.214	1.384	0.206	1.266	0.182	1.504	0.181	1.383	0.206	1.487	0.205	1.311
0.394	1	0.216	1.466	0.209	1.342	0.197	1.458	0.197	1.441	0.223	1.654	0.222	1.515
0.492	1.25	0.207	1.373	0.200	1.317	0.203	1.512	0.202	1.736	0.227	1.745	0.225	1.530
0.591	1.5	0.196	1.748	0.189	1.472	0.203	1.718	0.202	1.647	0.221	2.201	0.218	1.593
0.689	1.75	0.183	1.580	0.177	1.570	0.198	1.436	0.199	1.834	0.212	1.903	0.212	1.765
0.787	2	0.171	1.638	0.165	1.457	0.193	1.548	0.194	1.618	0.205	1.583	0.203	1.837
0.886	2.25	0.161	1.517	0.155	1.405	0.187	1.501	0.187	1.576	0.196	1.613	0.195	1.567
0.984	2.5	0.153	1.434	0.147	1.288	0.179	1.370	0.179	1.412	0.188	1.450	0.187	1.321
1.083	2.75	0.147	1.306	0.141	1.226	0.170	1.401	0.168	1.470	0.179	1.352	0.178	1.152
1.181	3	0.142	1.232	0.137	1.161	0.160	1.358	0.158	1.329	0.171	1.264	0.170	1.179
1.280	3.25	0.138	1.154	0.134	0.967	0.153	1.173	0.150	1.163	0.164	1.210	0.164	1.314
1.378	3.5	0.136	1.184	0.132	0.980	0.147	1.107	0.146	1.131	0.162	1.104	0.160	1.109
1.476	3.75	0.135	0.983	0.131	0.928	0.144	0.976	0.143	1.033	0.157	1.105	0.157	1.211
1.575	4	0.137	0.919	0.130	0.884	0.142	0.938	0.141	0.947	0.156	1.029	0.156	1.109
1.673	4.25	0.134	0.770	0.128	0.764	0.139	0.851	0.138	0.863	0.151	0.914	0.150	0.828
1.772	4.5	0.129	0.493	0.124	0.490	0.131	0.603	0.130	0.609	0.142	0.640	0.142	0.592

Figure AIII-7. Tunnel 3F (Low Velocity)

		Tunnel 3F				Tunnel 3F			
		Position D				Position E			
		Q16T35H40R1		Q16T35H40R2		Q16T35H40R1		Q16T35H40R2	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.210	0.664	0.210	0.660	0.146	0.572	0.145	0.600
0.098	0.25	0.242	0.836	0.240	0.971	0.164	0.923	0.162	1.053
0.148	0.376	0.274	0.904	0.272	1.107	0.184	1.143	0.183	1.308
0.197	0.5	0.297	1.172	0.296	1.143	0.202	1.226	0.201	1.412
0.246	0.625	0.314	0.954	0.311	1.109	0.216	1.289	0.214	1.434
0.295	0.75	0.322	1.027	0.319	1.142	0.224	1.290	0.223	1.463
0.394	1	0.321	1.109	0.319	1.184	0.229	1.347	0.228	1.492
0.492	1.25	0.309	1.286	0.306	1.267	0.221	1.493	0.220	1.616
0.591	1.5	0.293	1.489	0.292	1.304	0.209	1.443	0.207	1.621
0.689	1.75	0.274	1.396	0.273	1.648	0.195	1.343	0.194	1.516
0.787	2	0.258	1.481	0.255	1.395	0.182	1.461	0.183	1.460
0.886	2.25	0.241	1.295	0.238	1.474	0.172	1.355	0.172	1.521
0.984	2.5	0.226	1.164	0.224	1.309	0.165	1.383	0.165	1.370
1.083	2.75	0.214	1.208	0.214	1.311	0.160	1.163	0.160	1.270
1.181	3	0.206	1.131	0.206	1.142	0.157	1.217	0.157	1.256
1.280	3.25	0.201	0.980	0.201	1.222	0.155	1.246	0.155	1.217
1.378	3.5	0.199	0.964	0.198	0.998	0.154	1.188	0.153	1.170
1.476	3.75	0.197	0.894	0.196	0.953	0.153	1.139	0.152	1.127
1.575	4	0.196	0.843	0.194	0.907	0.152	1.086	0.151	1.081
1.673	4.25	0.193	0.701	0.192	0.748	0.149	0.949	0.148	0.967
1.772	4.5	0.188	0.532	0.187	0.545	0.142	0.649	0.141	0.707

Figure AIII-7. (Continued). Tunnel 3F (Low Velocity Continued)

Probe Height		Data for Tunnel 3F				Tunnel 3F				Tunnel 3F			
		Position A				Position B				Position C			
		Q153T35H50R2		Q153T35H50R3		Q153T35H50R1		Q153T35H50R2		Q137T35H50R1		Q137T35H50R2	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.05	0.127							0.890	15.341	1.001	16.630	0.993	16.935
0.098	0.25	1.222	15.043	1.241	14.045	1.122	13.005	1.137	14.805	1.280	15.534	1.288	14.284
0.148	0.376	1.366	12.729	1.344	12.341	1.276	12.191	1.264	12.560	1.448	12.214	1.395	14.038
0.197	0.5	1.418	11.514	1.448	9.947	1.367	9.969	1.368	9.150	1.488	11.615	1.473	11.263
0.246	0.625	1.508	9.084	1.473	9.464	1.407	8.439	1.410	8.939	1.563	9.900	1.538	9.665
0.295	0.75	1.545	8.647	1.534	8.138	1.432	7.633	1.455	7.779	1.586	8.714	1.573	8.486
0.394	1	1.605	7.974	1.593	6.802	1.457	7.688	1.457	7.592	1.632	7.814	1.631	7.872
0.492	1.25	1.648	6.413	1.627	6.125	1.459	7.844	1.456	8.372	1.687	7.237	1.661	7.379
0.591	1.5	1.680	5.712	1.657	5.670	1.436	9.568	1.424	9.162	1.707	6.818	1.700	7.007
0.689	1.75	1.706	4.692	1.674	5.554	1.446	8.816	1.397	9.194	1.713	7.506	1.703	7.193
0.787	2	1.699	5.458	1.692	4.713	1.408	9.556	1.410	9.652	1.737	7.067	1.733	6.541
0.886	2.25	1.726	4.901	1.690	4.984	1.418	9.436	1.417	9.419	1.728	6.782	1.726	7.070
0.984	2.5	1.730	4.587	1.708	3.902	1.452	9.321	1.465	9.463	1.790	5.846	1.731	6.516
1.083	2.75	1.714	4.396	1.706	3.761	1.483	9.155	1.484	8.596	1.790	5.601	1.756	5.574
1.181	3	1.713	4.418	1.692	3.914	1.524	6.958	1.513	7.871	1.742	6.064	1.741	5.927
1.280	3.25	1.720	3.790	1.697	4.193	1.543	6.774	1.553	6.190	1.748	5.986	1.731	6.410
1.378	3.5	1.711	4.370	1.694	3.955	1.552	6.468	1.528	6.434	1.716	6.580	1.727	6.501
1.476	3.75	1.669	5.435	1.650	4.924	1.533	6.693	1.506	7.320	1.725	6.529	1.697	6.511
1.575	4	1.600	7.391	1.594	6.410	1.454	8.556	1.431	9.543	1.670	7.390	1.621	7.376
1.673	4.25	1.465	11.223	1.419	11.790	1.264	13.470	1.279	12.764	1.525	10.294	1.525	10.526
1.772	4.5	1.172	16.984	1.095	18.153	0.953	20.044	0.939	20.399	1.284	13.433	1.294	14.083

Figure AIII.7. (Continued). Tunnel 3F (Medium Velocity)

		Tunnel 3F				Tunnel 3F	
		Position D				Position E	
		Q153T35H50R1		Q153T35H50R2		Q153T35H50R1	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.05	0.127	0.886	19.978	0.857	16.931	0.995	15.935
0.098	0.25	1.115	16.440	1.108	16.442	1.192	14.204
0.148	0.376	1.256	13.049	1.248	13.152	1.291	13.894
0.197	0.5	1.314	11.253	1.321	10.136	1.367	10.343
0.246	0.625	1.365	10.204	1.345	9.891	1.421	9.701
0.295	0.75	1.430	8.462	1.405	9.068	1.439	8.361
0.394	1	1.486	7.260	1.460	7.488	1.515	7.321
0.492	1.25	1.536	6.575	1.504	7.007	1.573	6.118
0.591	1.5	1.573	6.152	1.552	5.987	1.596	5.320
0.689	1.75	1.598	5.153	1.581	4.853	1.620	5.249
0.787	2	1.614	4.372	1.601	4.363	1.638	4.141
0.886	2.25	1.617	4.213	1.610	3.754	1.640	3.905
0.984	2.5	1.621	3.703	1.602	3.686	1.639	3.505
1.083	2.75	1.629	3.424	1.602	3.349	1.641	3.603
1.181	3	1.618	3.095	1.601	3.348	1.629	3.549
1.280	3.25	1.619	3.579	1.608	3.310	1.630	3.237
1.378	3.5	1.612	3.643	1.590	3.826	1.611	3.355
1.476	3.75	1.578	4.017	1.571	4.412	1.592	4.280
1.575	4	1.528	6.576	1.516	6.669	1.539	6.966
1.673	4.25	1.416	7.869	1.396	9.267	1.405	10.650
1.772	4.5	1.099	16.698	1.118	16.412	1.147	16.449

Figure AIII.7. (Continued). Tunnel 3F (Medium Velocity Continued)

Probe Height		Data for Tunnel 3F Position A				Tunnel 3F Position B				Tunnel 3F Position C			
		Q365T35H50R1		Q365T35H50R1		Q365T35H50R2		Q365T35H50R3		Q303T35H50R1		Q303T35H50R2	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)		(m/s)		(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127					2.1415	14.813	2.1745	14.864	2.341	15.812	2.272	16.167
0.098	0.25	2.673	12.524	2.696	13.628	2.479	11.944	2.436	12.134	2.615	12.730	2.543	13.524
0.148	0.376	2.837	10.978	2.854	11.367	2.669	9.652	2.654	9.939	2.764	12.766	2.789	12.838
0.197	0.5	2.981	10.398	3.001	9.350	2.761	8.499	2.745	8.780	2.972	11.392	2.984	10.986
0.246	0.625	3.015	9.313	3.057	9.077	2.890	7.946	2.862	7.663	3.088	10.024	3.074	10.393
0.295	0.75	3.127	8.729	3.124	8.328	2.941	7.789	2.931	7.460	3.142	9.053	3.141	9.322
0.394	1	3.280	7.424	3.277	7.389	3.079	7.034	3.026	8.003	3.319	8.921	3.350	9.129
0.492	1.25	3.400	6.678	3.394	6.498	3.066	7.880	3.040	7.601	3.390	7.310	3.394	7.849
0.591	1.5	3.499	5.930	3.476	6.025	3.049	8.381	3.083	8.640	3.474	7.205	3.516	6.725
0.689	1.75	3.547	4.807	3.544	5.108	3.048	8.545	3.023	8.739	3.508	6.692	3.556	6.645
0.787	2	3.588	4.916	3.596	4.336	3.056	8.674	3.124	8.774	3.555	6.259	3.600	6.491
0.886	2.25	3.583	4.605	3.604	3.879	3.070	8.514	3.064	9.001	3.588	6.248	3.625	6.086
0.984	2.5	3.569	5.096	3.615	4.400	3.119	8.572	3.184	7.810	3.525	6.453	3.637	5.515
1.083	2.75	3.582	4.496	3.602	3.835	3.190	7.992	3.187	8.434	3.595	6.212	3.610	5.660
1.181	3	3.598	3.572	3.580	4.041	3.225	7.185	3.218	6.830	3.653	6.097	3.502	6.416
1.280	3.25	3.568	4.052	3.563	3.846	3.263	6.835	3.239	6.508	3.630	6.468	3.555	6.360
1.378	3.5	3.537	4.244	3.503	4.274	3.248	5.642	3.235	6.243	3.507	5.611	3.592	6.453
1.476	3.75	3.448	5.090	3.441	5.323	3.142	6.227	3.149	6.563	3.413	6.470	3.464	7.275
1.575	4	3.326	6.455	3.324	6.508	3.021	7.704	2.999	7.583	3.350	6.702	3.413	6.919
1.673	4.25	3.101	9.130	3.079	9.498	2.761	10.467	2.747	10.471	3.171	8.473	3.168	8.231
1.772	4.5	2.623	14.213	2.623	14.213	2.358	15.589	2.293	16.082	2.868	12.371	2.935	11.878

Figure AIII.7. (Continued). Tunnel 3F (High Velocity)

		Tunnel 3F				Tunnel 3F	
		Position D				Position E	
		Q365T35H50R1		Q365T35H50R2		Q365T35H50R1	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	2.2499	17.236	2.2028	16.912	2.3688	15.739
0.098	0.25	2.599	13.421	2.546	14.114	2.678	11.879
0.148	0.376	2.777	11.910	2.761	11.587	2.824	10.909
0.197	0.5	2.913	10.212	2.850	10.302	2.966	9.814
0.246	0.625	3.037	9.547	2.927	9.308	3.024	9.150
0.295	0.75	3.070	8.404	3.064	8.731	3.120	8.405
0.394	1	3.227	8.000	3.144	8.101	3.259	7.719
0.492	1.25	3.346	7.161	3.290	7.100	3.372	6.423
0.591	1.5	3.445	6.138	3.441	5.771	3.481	5.689
0.689	1.75	3.549	5.111	3.474	5.242	3.557	4.570
0.787	2	3.591	4.324	3.533	4.314	3.582	4.428
0.886	2.25	3.589	3.921	3.558	3.803	3.594	3.840
0.984	2.5	3.612	3.892	3.547	3.746	3.601	3.898
1.083	2.75	3.585	3.378	3.561	3.705	3.580	3.519
1.181	3	3.573	3.397	3.535	3.776	3.577	3.564
1.280	3.25	3.533	3.538	3.494	3.637	3.534	4.082
1.378	3.5	3.461	4.429	3.455	4.133	3.479	4.132
1.476	3.75	3.396	4.565	3.355	4.700	3.385	5.062
1.575	4	3.254	6.352	3.229	5.922	3.235	6.567
1.673	4.25	3.027	8.684	3.033	8.383	2.999	10.436
1.772	4.5	2.624	13.710	2.569	15.038	2.528	14.760

Figure AIII.7. (Continued). Tunnel 3F (High Velocity Continued)

Probe Height		Tunnel 3F							
		Medium Velocity				Low Velocity			
		Room Temperature		35 deg C		Room Temperature		35 deg C	
		Q198T25R4B		Q153T35H50R2		Q30T25R1		Q10T35R1	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.05	0.127					0.10723	0.57435	0.1694	0.45431
0.098425	0.25	1.1894	17.92	1.2218	15.043	0.12096	1.209	0.16506	0.79754
0.148	0.376	1.318	14.771	1.3663	12.729	0.13632	1.4122	0.17674	1.0843
0.19685	0.5	1.3545	14.258	1.4176	11.514	0.15459	1.7011	0.18872	1.1686
0.246	0.625	1.4432	11.392	1.5078	9.0838	0.17236	1.9851	0.19881	1.4476
0.295276	0.75	1.4914	10.339	1.5453	8.6469	0.18622	2.2486	0.21088	1.517
0.393701	1	1.5646	8.4188	1.605	7.9743	0.21482	2.8748	0.22673	1.6617
0.492126	1.25	1.6152	7.385	1.648	6.4128	0.23538	2.6536	0.23723	1.5569
0.590551	1.5	1.6533	6.6027	1.68	5.7119	0.25105	2.183	0.23865	1.6088
0.688976	1.75	1.6654	6.3187	1.7062	4.6922	0.25748	2.2053	0.23338	1.7302
0.787402	2	1.6855	5.8937	1.699	5.4575	0.2614	2.5251	0.225	1.7267
0.885827	2.25	1.6927	5.6207	1.7256	4.9013	0.26371	2.2217	0.21708	1.6994
0.984252	2.5	1.6907	5.6904	1.7298	4.5866	0.26241	2.2579	0.2081	1.5854
1.082677	2.75	1.6961	5.4858	1.7142	4.3958	0.26123	2.5571	0.20066	1.6234
1.181102	3	1.6836	5.0464	1.7134	4.4184	0.26167	2.3326	0.19565	1.6087
1.279528	3.25	1.7018	4.9177	1.7204	3.7898	0.25884	2.2112	0.19143	1.5411
1.377953	3.5	1.6789	4.9297	1.7114	4.3697	0.24926	2.409	0.18902	1.4823
1.476378	3.75	1.6661	5.2368	1.6693	5.4354	0.23948	2.4586	0.18741	1.4352
1.574803	4	1.6261	6.9265	1.6004	7.3905	0.2107	2.3291	0.18546	1.3578
1.673228	4.25	1.5214	10.001	1.4652	11.223	0.1738	3.1162	0.18588	1.1911
1.772	4.5	1.3145	15.96	1.1719	16.984	0.12738	2.3768	0.18038	0.81381

Figure AIII.8. Tunnel 3F Measurements – Effect of Temperature

Probe Height		Tunnel 3F Position A Substrate Concrete Waves Perp to Flow				Tunnel 3F Position A Substrate Concrete Waves Par to Flow			
		Q16T35H41SCR1		Q16T35H41SCR2		Q16T35H41SCR4		Q16T35H41SCR4	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.140	0.737	0.140	0.808	0.1423	0.7126	0.148	0.623
0.098	0.25	0.156	1.058	0.157	1.270	0.1626	1.0327	0.168	0.936
0.148	0.376	0.178	1.443	0.177	1.428	0.1829	1.3632	0.189	1.089
0.197	0.5	0.194	1.543	0.194	1.581	0.2007	1.4247	0.207	1.278
0.246	0.625	0.206	1.594	0.205	1.608	0.2128	1.4361	0.220	1.238
0.295	0.75	0.213	1.592	0.212	1.658	0.2215	1.474	0.229	1.244
0.394	1	0.217	1.622	0.215	1.628	0.2234	1.5995	0.229	1.304
0.492	1.25	0.208	1.583	0.206	1.605	0.2153	1.6022	0.220	1.383
0.591	1.5	0.196	1.660	0.194	1.630	0.203	1.7705	0.208	1.552
0.689	1.75	0.184	1.584	0.182	1.648	0.1898	1.931	0.195	1.634
0.787	2	0.171	1.529	0.169	1.500	0.1781	1.7243	0.181	1.709
0.886	2.25	0.161	1.497	0.159	1.527	0.1662	1.557	0.170	1.396
0.984	2.5	0.152	1.286	0.151	1.336	0.157	1.5649	0.161	1.303
1.083	2.75	0.146	1.277	0.145	1.269	0.1502	1.4254	0.154	1.406
1.181	3	0.142	1.133	0.140	1.166	0.1454	1.3668	0.149	1.270
1.280	3.25	0.138	1.163	0.137	1.085	0.1429	1.2636	0.145	1.213
1.378	3.5	0.137	1.030	0.136	1.075	0.1414	1.2197	0.143	1.114
1.476	3.75	0.136	0.998	0.135	1.019	0.1398	1.1418	0.142	1.055
1.575	4	0.136	0.909	0.134	0.910	0.1384	1.0575	0.142	0.966
1.673	4.25	0.134	0.788	0.133	0.778	0.1369	0.8729	0.140	0.864
1.772	4.5	0.130	0.558	0.128	0.509	0.1325	0.5783	0.135	0.555

Figure AIII.9. Tunnel 3F – Effect of Surface Roughness (Low Velocity)

		Tunnel 3F				Tunnel 3F			
		Position A Substrate Concrete Waves Par to Flow				Position A Substrate Concrete Waves Perp to Flow			
		Q165T35H25SCR3		Q165T35H25SCR4		Q165T35H25SCR1		Q165T35H25SCR2	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.05	0.127	1.053	18.227	1.061	18.943	0.9756	19.256	0.957	20.152
0.098	0.25	1.264	16.332	1.215	16.226	1.1826	17.434	1.193	16.882
0.148	0.376	1.383	13.467	1.341	14.336	1.3367	14.467	1.340	13.842
0.197	0.5	1.453	12.363	1.451	11.946	1.4212	12.632	1.426	12.466
0.246	0.625	1.485	10.990	1.508	9.694	1.4866	10.774	1.473	10.786
0.295	0.75	1.552	8.897	1.548	9.354	1.5403	9.7197	1.545	9.608
0.394	1	1.619	7.551	1.615	7.741	1.6117	7.8613	1.584	8.373
0.492	1.25	1.652	6.693	1.658	6.640	1.6593	6.7093	1.656	6.531
0.591	1.5	1.706	5.735	1.690	5.790	1.7232	5.3638	1.702	5.802
0.689	1.75	1.730	4.567	1.721	4.839	1.731	5.1663	1.714	4.588
0.787	2	1.753	4.147	1.734	4.477	1.7429	4.2102	1.734	4.351
0.886	2.25	1.732	3.947	1.736	3.763	1.7619	3.684	1.745	3.912
0.984	2.5	1.730	4.195	1.731	3.633	1.7493	3.8061	1.732	3.410
1.083	2.75	1.729	3.819	1.717	3.479	1.7412	4.0464	1.726	3.631
1.181	3	1.726	3.570	1.715	3.512	1.7272	3.4641	1.724	3.442
1.280	3.25	1.710	4.024	1.707	3.327	1.7195	3.5109	1.724	3.534
1.378	3.5	1.696	3.992	1.666	4.506	1.6928	3.7953	1.687	4.389
1.476	3.75	1.627	5.765	1.633	5.684	1.666	5.1072	1.647	4.971
1.575	4	1.578	7.589	1.559	8.027	1.5998	6.8941	1.571	7.526
1.673	4.25	1.418	11.313	1.428	11.703	1.4803	11.025	1.443	10.796
1.772	4.5	1.112	17.308	1.104	17.666	1.1901	15.842	1.204	16.479

Figure AIII.9. (Continued). Tunnel 3F - Effect of Surface Roughness (Medium Velocity)

		Tunnel 3F				Tunnel 3F			
		Position A Substrate Concrete Waves Perp to Flow				Position A Substrate Concrete Waves Par to Flow			
		Q381T35H31SCR1		Q381T35H31SCR2		Q381T35H31SCR3		Q381T35H31SCR4	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	2.510	13.747	2.475	13.784	2.5142	14.056	2.496	13.956
0.098	0.25	2.746	12.193	2.713	12.004	2.7281	11.381	2.724	11.885
0.148	0.376	2.852	10.949	2.842	11.270	2.8721	10.74	2.892	10.556
0.197	0.5	3.023	10.662	3.013	9.571	3.0173	9.5968	2.991	10.560
0.246	0.625	3.130	9.092	3.140	9.005	3.1178	8.9918	3.098	9.229
0.295	0.75	3.215	8.634	3.217	8.160	3.2158	8.243	3.206	7.752
0.394	1	3.358	7.361	3.326	7.347	3.3548	6.8777	3.314	7.218
0.492	1.25	3.488	6.302	3.438	6.157	3.4481	6.2177	3.435	6.226
0.591	1.5	3.570	5.569	3.535	5.526	3.5411	5.3021	3.522	5.205
0.689	1.75	3.617	4.705	3.599	4.776	3.5884	4.5996	3.579	4.497
0.787	2	3.656	4.159	3.629	4.083	3.6144	3.9864	3.618	4.171
0.886	2.25	3.664	3.776	3.633	3.839	3.6041	4.0424	3.602	3.774
0.984	2.5	3.650	3.484	3.621	3.926	3.6234	3.7972	3.606	3.753
1.083	2.75	3.652	3.758	3.616	3.530	3.6097	3.8236	3.598	3.699
1.181	3	3.628	3.724	3.589	3.692	3.5906	3.8261	3.576	3.895
1.280	3.25	3.570	3.846	3.552	3.883	3.5373	3.5735	3.538	4.187
1.378	3.5	3.506	3.972	3.494	4.402	3.4795	4.4104	3.480	4.036
1.476	3.75	3.438	4.862	3.412	4.985	3.389	5.0525	3.388	5.180
1.575	4	3.296	6.434	3.276	6.378	3.2498	6.4373	3.254	6.429
1.673	4.25	3.060	8.654	3.055	8.550	3.0311	8.9086	3.042	8.751
1.772	4.5	2.662	14.012	2.736	12.526	2.6429	14.242	2.661	13.865

Figure AIII.9. (Continued)Tunnel 3F – Effect of Surface Roughness (High Velocity)

		Tunnel 3G				Tunnel 3G				Tunnel 3G			
		Position A				Position A				Position A			
		Q25T35H5R1		Q25T35H5R2		Q177T35H18R1		Q177T35H18R2		Q396T35H10R1		Q396T35H10R2	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.121	0.396	0.122	0.435	0.912	22.669	0.894	22.213	2.330	15.365	2.343	16.057
0.098	0.25	0.145	0.885	0.146	1.137	1.184	17.462	1.162	17.850	2.692	11.970	2.659	12.269
0.148	0.376	0.171	1.234	0.173	1.566	1.350	13.290	1.308	14.762	2.887	10.278	2.840	10.312
0.197	0.5	0.195	1.181	0.194	1.707	1.423	11.837	1.425	11.123	2.960	9.610	2.936	9.774
0.246	0.625	0.212	1.360	0.215	1.376	1.487	10.070	1.468	9.422	3.031	8.631	3.022	8.613
0.295	0.75	0.226	1.475	0.229	1.050	1.501	9.785	1.501	9.689	3.108	8.215	3.140	7.926
0.394	1	0.244	1.050	0.245	1.097	1.580	7.780	1.581	8.139	3.252	7.279	3.233	7.508
0.492	1.25	0.249	0.856	0.250	0.804	1.623	7.173	1.624	7.383	3.371	6.735	3.367	6.463
0.591	1.5	0.251	0.887	0.251	0.954	1.664	6.458	1.680	5.735	3.460	5.860	3.450	5.882
0.689	1.75	0.248	1.008	0.250	1.241	1.713	4.930	1.701	5.051	3.541	4.919	3.522	5.106
0.787	2	0.245	0.786	0.248	0.876	1.727	4.416	1.715	4.489	3.564	4.638	3.567	4.431
0.886	2.25	0.240	1.116	0.243	1.012	1.725	4.098	1.719	4.382	3.586	4.263	3.594	4.001
0.984	2.5	0.234	1.345	0.233	1.272	1.738	4.126	1.714	4.198	3.607	3.942	3.567	3.956
1.083	2.75	0.225	1.208	0.223	1.186	1.731	3.891	1.725	3.958	3.584	3.765	3.567	4.101
1.181	3	0.208	1.294	0.209	1.112	1.725	4.109	1.718	3.832	3.573	3.686	3.572	3.757
1.280	3.25	0.192	1.721	0.191	0.976	1.719	3.956	1.715	3.583	3.555	3.755	3.541	3.732
1.378	3.5	0.172	1.008	0.175	1.310	1.700	4.189	1.691	4.201	3.501	3.913	3.496	4.067
1.476	3.75	0.154	0.647	0.157	1.043	1.653	5.987	1.647	5.671	3.429	4.662	3.399	4.953
1.575	4	0.140	0.761	0.140	0.644	1.574	8.457	1.581	7.579	3.296	6.695	3.260	6.565
1.673	4.25	0.125	0.483	0.126	0.435	1.417	14.144	1.427	12.008	2.967	10.026	2.987	10.117
1.772	4.5	0.114	0.241	0.114	0.213	1.148	19.936	1.122	22.297	2.561	13.795	2.536	13.961

Figure AIII-10. Tunnel 3G

		(q=170)				(q=422)			
		Position A				Position A			
		VertInlet		VertInlet2		VertInlet3		VertInlet4	
Probe Height		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	1.102	20.580	1.038	21.156	2.583	13.737	2.585	14.463
0.098	0.25	1.273	16.910	1.278	15.837	2.707	13.360	2.723	12.892
0.148	0.376	1.403	13.054	1.378	13.682	2.855	10.936	2.891	11.216
0.197	0.5	1.480	11.632	1.410	12.847	2.983	10.248	2.971	10.880
0.246	0.625	1.511	10.436	1.490	10.668	3.067	9.234	3.035	9.115
0.295	0.75	1.541	9.739	1.534	9.823	3.176	8.526	3.130	8.592
0.394	1	1.630	7.521	1.626	7.685	3.305	8.321	3.343	7.956
0.492	1.25	1.659	6.639	1.659	5.982	3.442	6.688	3.440	6.577
0.591	1.5	1.701	5.099	1.677	5.705	3.557	5.243	3.558	5.843
0.689	1.75	1.700	4.331	1.695	5.207	3.621	4.668	3.618	4.624
0.787	2	1.672	4.865	1.680	4.859	3.621	4.357	3.624	4.322
0.886	2.25	1.649	5.021	1.648	4.907	3.622	4.161	3.624	4.238
0.984	2.5	1.619	5.313	1.604	5.317	3.560	4.745	3.559	4.378
1.083	2.75	1.552	6.261	1.576	6.303	3.550	4.908	3.506	5.693
1.181	3	1.541	6.740	1.532	7.896	3.454	5.577	3.432	6.112
1.280	3.25	1.486	7.811	1.480	7.485	3.387	6.804	3.420	6.141
1.378	3.5	1.399	10.196	1.382	10.155	3.335	6.874	3.306	7.270
1.476	3.75	1.300	11.653	1.311	12.101	3.256	7.532	3.222	7.069
1.575	4	1.174	16.178	1.233	15.084	3.137	9.055	3.103	7.714
1.673	4.25	1.011	21.224	0.985	23.175	2.950	11.116	2.906	10.919
1.772	4.5	0.678	29.790	0.659	29.728	2.520	15.568	2.428	16.695

Figure AIII-10. (Continued). Tunnel 3G

Probe Height		Tunnel 3I Position A				Tunnel 3I Position A				Tunnel 3I Position A			
		Q173T35H31R1		Q173T35H31R2		Q388T35H21R1		Q388T35H21R2		Q12T35H20R1		Q12T35H20R2	
(in)	(cm)	Velocity (m/s)	Turb Int. (%)	Velocity (m/s)	Turb Int. (%)	Velocity (m/s)	Turb Int. (%)	Velocity (m/s)	Turb Int. (%)	Velocity (m/s)	Turb Int. (%)	Velocity (m/s)	Turb Int. (%)
0.050	0.127	1.007	19.389	1.004	19.193	2.470	14.772	2.460	14.923	0.124	0.499	0.122	0.821
0.098	0.25	1.243	15.923	1.256	15.998	2.706	12.286	2.698	12.589	0.146	0.639	0.145	0.345
0.148	0.376	1.381	12.444	1.402	12.726	2.885	11.567	2.897	11.278	0.171	0.342	0.172	0.292
0.197	0.5	1.462	10.835	1.460	10.812	3.008	10.678	3.020	10.365	0.191	0.283	0.192	0.420
0.246	0.625	1.501	10.231	1.510	9.481	3.154	9.146	3.154	9.036	0.205	0.530	0.206	0.638
0.295	0.75	1.566	8.681	1.562	8.635	3.255	8.344	3.210	8.806	0.213	0.306	0.213	0.365
0.394	1	1.633	7.510	1.633	6.819	3.399	7.441	3.404	7.338	0.212	0.622	0.212	0.382
0.492	1.25	1.681	5.753	1.692	5.781	3.521	6.370	3.541	6.054	0.201	0.610	0.201	0.638
0.591	1.5	1.721	4.064	1.720	4.088	3.621	4.776	3.619	4.712	0.185	0.486	0.184	0.607
0.689	1.75	1.726	3.299	1.724	3.483	3.666	3.658	3.661	3.769	0.169	0.441	0.169	0.621
0.787	2	1.719	2.729	1.716	2.709	3.667	2.966	3.665	3.189	0.154	0.690	0.155	0.632
0.886	2.25	1.699	2.580	1.699	2.586	3.650	2.713	3.640	2.847	0.142	0.492	0.142	0.593
0.984	2.5	1.673	2.485	1.677	2.350	3.609	2.700	3.602	2.693	0.132	0.822	0.133	0.715
1.083	2.75	1.656	2.598	1.655	2.384	3.566	2.930	3.544	2.818	0.125	0.396	0.125	0.630
1.181	3	1.621	2.500	1.631	2.454	3.505	2.859	3.498	2.750	0.120	0.852	0.121	0.782
1.280	3.25	1.598	2.653	1.599	2.652	3.441	3.283	3.446	3.250	0.116	0.879	0.116	0.876
1.378	3.5	1.565	2.942	1.562	3.632	3.384	3.704	3.381	3.607	0.113	0.330	0.113	0.309
1.476	3.75	1.517	4.456	1.517	4.587	3.288	5.071	3.285	4.991	0.109	0.890	0.110	0.840
1.575	4	1.415	6.641	1.405	7.023	3.160	6.469	3.157	6.641	0.107	0.639	0.107	0.819
1.673	4.25	1.236	9.011	1.223	10.278	2.952	10.003	2.927	9.916	0.102	0.783	0.102	0.451
1.772	4.5	0.931	10.634	0.869	11.944	2.487	15.320	2.497	15.849	0.095	0.941	0.094	0.892

Figure AIII-11. Tunnel 3I

Probe Height		Tunnel 3J				Tunnel 3J				Tunnel 3J			
		Position A				Position A				Position A			
		Q163T35H29R1		Q163T35H29R2		Q381T35H20R1		Q381T35H20R2		Q11T35H23R1		Q11T35H23R2	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	1.040	18.681	1.040	18.764	2.507	13.530	2.551	14.518	0.135	0.810	0.135	0.431
0.098	0.25	1.250	15.814	1.291	13.093	2.706	12.658	2.753	12.027	0.153	0.638	0.154	0.717
0.148	0.376	1.365	12.973	1.407	12.247	2.867	11.675	2.930	11.722	0.175	0.603	0.176	0.702
0.197	0.5	1.458	10.287	1.429	11.092	3.022	10.335	3.023	10.890	0.193	0.627	0.193	0.522
0.246	0.625	1.496	10.014	1.491	9.808	3.192	9.717	3.144	10.073	0.205	0.405	0.206	0.289
0.295	0.75	1.548	7.695	1.535	8.605	3.263	8.980	3.304	8.686	0.213	0.236	0.213	0.619
0.394	1	1.690	6.729	1.682	7.270	3.487	7.669	3.578	7.602	0.238	1.949	0.255	2.280
0.492	1.25	1.639	5.971	1.653	6.045	3.552	6.256	3.625	6.397	0.206	2.518	0.226	3.139
0.591	1.5	1.676	4.057	1.671	4.561	3.666	4.606	3.717	4.714	0.189	0.677	0.189	0.547
0.689	1.75	1.681	3.246	1.673	3.474	3.710	3.618	3.748	3.815	0.174	0.409	0.173	0.574
0.787	2	1.672	2.884	1.668	3.040	3.714	3.104	3.748	2.910	0.161	0.672	0.161	0.333
0.886	2.25	1.650	2.485	1.651	2.567	3.684	2.594	3.727	2.698	0.151	0.662	0.150	0.453
0.984	2.5	1.633	2.519	1.626	2.603	3.649	2.598	3.693	2.424	0.142	0.757	0.141	0.421
1.083	2.75	1.608	2.377	1.611	2.118	3.610	2.579	3.654	2.524	0.136	0.747	0.135	0.673
1.181	3	1.599	2.135	1.595	2.074	3.567	2.773	3.596	2.773	0.131	0.412	0.130	0.371
1.280	3.25	1.586	1.790	1.580	1.950	3.506	3.177	3.535	3.267	0.129	0.798	0.127	0.834
1.378	3.5	1.567	2.442	1.568	2.344	3.402	4.202	3.443	4.231	0.126	0.704	0.124	0.295
1.476	3.75	1.537	3.082	1.527	3.434	3.301	5.559	3.317	5.575	0.123	0.708	0.122	0.315
1.575	4	1.454	4.453	1.457	4.719	3.135	7.182	3.169	6.832	0.121	0.225	0.120	0.369
1.673	4.25	1.285	7.273	1.258	7.795	2.878	10.168	2.937	9.947	0.116	0.536	0.115	0.278
1.772	4.5	0.922	9.148	0.924	7.435	2.497	15.320	2.573	15.003	0.111	0.365	0.109	0.909

Figure AIII-12. Tunnel 3J

	Tunnel 3K				Tunnel 3K				Tunnel 3K			
	Position A				Position A				Position A			
	Q11T35H8R1		Q11T35H8R2		Q177T35H32R1		Q177T35H32R2		Q407T35H23R1		Q407T35H23R2	
Height	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.127	0.133	0.641	0.131	0.636	0.964	19.445	0.978	17.279	2.400	15.816	2.399	16.077
0.25	0.152	0.642	0.151	0.596	1.215	16.562	1.256	15.214	2.781	12.267	2.736	12.198
0.376	0.175	0.499	0.175	0.300	1.358	12.444	1.373	13.267	2.947	10.026	2.939	9.984
0.5	0.193	0.517	0.194	0.268	1.434	10.858	1.449	9.738	3.060	9.075	3.039	9.193
0.625	0.204	0.268	0.204	0.435	1.481	9.662	1.469	9.830	3.112	8.704	3.125	8.468
0.75	0.210	0.429	0.210	0.588	1.542	8.748	1.558	8.050	3.204	8.026	3.203	8.136
1	0.212	0.543	0.212	0.431	1.596	7.481	1.612	7.628	3.348	7.147	3.324	7.210
1.25	0.207	0.428	0.206	0.434	1.668	5.564	1.660	5.939	3.460	6.209	3.481	5.853
1.5	0.200	0.427	0.200	0.415	1.698	4.791	1.703	4.642	3.588	4.962	3.577	5.112
1.75	0.194	0.670	0.194	0.644	1.719	3.824	1.730	3.620	3.653	4.031	3.652	3.788
2	0.187	0.453	0.187	0.502	1.739	3.011	1.746	2.728	3.697	2.823	3.682	3.091
2.25	0.179	0.664	0.178	0.679	1.744	2.356	1.745	2.362	3.711	2.386	3.695	2.445
2.5	0.172	0.503	0.171	0.388	1.740	2.243	1.743	2.202	3.707	2.288	3.699	2.238
2.75	0.165	0.246	0.164	0.446	1.731	2.142	1.732	2.222	3.691	2.356	3.684	2.421
3	0.156	0.744	0.155	0.536	1.722	2.472	1.719	2.561	3.656	2.824	3.649	2.666
3.25	0.149	0.734	0.148	0.333	1.697	2.917	1.700	3.109	3.598	3.477	3.604	3.257
3.5	0.143	0.541	0.141	0.543	1.672	3.516	1.670	3.844	3.534	4.150	3.540	3.990
3.75	0.136	0.812	0.135	0.528	1.612	5.916	1.627	5.100	3.436	5.002	3.434	4.956
4	0.130	0.832	0.128	0.714	1.548	7.404	1.536	8.002	3.293	6.833	3.288	6.618
4.25	0.122	0.442	0.120	0.297	1.363	10.905	1.376	10.833	3.112	9.651	3.087	9.308
4.5	0.112	0.514	0.110	0.887	1.009	13.426	1.024	16.318	2.762	14.619	2.733	14.813

Figure AIII-13. Tunnel 3K

Probe Height		Tunnel 3L				Tunnel 3L				Tunnel 3L			
		Position A				Position B		Position C		Position D		Position E	
		Q13T35H4R1		Q13T35H4R2		Q13T35H4R1		Q13T35H4R1		Q13T35H4R1		Q13T35H4R1	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	0.123	0.375	0.123	0.604	0.106	0.860	0.126	0.242	0.124	0.330	0.138	0.293
0.098	0.25	0.147	0.589	0.148	0.499	0.123	0.439	0.144	0.628	0.151	0.297	0.165	0.373
0.148	0.376	0.175	0.615	0.175	0.674	0.145	0.307	0.167	0.629	0.176	0.686	0.193	0.673
0.197	0.5	0.195	0.620	0.195	0.464	0.163	0.533	0.185	0.330	0.196	0.243	0.212	0.538
0.246	0.625	0.208	0.447	0.208	0.363	0.178	0.697	0.199	0.659	0.207	0.329	0.224	0.458
0.295	0.75	0.214	0.636	0.214	0.611	0.188	0.677	0.208	0.229	0.212	0.276	0.230	0.613
0.394	1	0.216	0.477	0.216	0.263	0.198	0.628	0.216	0.343	0.213	0.598	0.229	0.280
0.492	1.25	0.212	0.634	0.212	0.476	0.198	0.655	0.214	0.476	0.209	0.294	0.221	0.292
0.591	1.5	0.204	0.542	0.204	0.502	0.193	0.607	0.207	0.457	0.202	0.595	0.211	0.283
0.689	1.75	0.197	0.444	0.196	0.543	0.187	0.366	0.197	0.259	0.196	0.488	0.200	0.329
0.787	2	0.188	0.491	0.188	0.320	0.179	0.565	0.187	0.251	0.187	0.604	0.190	0.533
0.886	2.25	0.180	0.553	0.178	0.266	0.171	0.209	0.176	0.600	0.179	0.426	0.180	0.458
0.984	2.5	0.171	0.296	0.169	0.510	0.162	0.730	0.166	0.726	0.169	0.641	0.171	0.568
1.083	2.75	0.162	0.265	0.160	0.287	0.154	0.565	0.157	0.408	0.159	0.633	0.164	0.294
1.181	3	0.152	0.282	0.152	0.492	0.145	0.533	0.149	0.774	0.149	0.466	0.158	0.442
1.280	3.25	0.145	0.355	0.143	0.564	0.135	0.799	0.141	0.420	0.138	0.334	0.153	0.619
1.378	3.5	0.136	0.686	0.135	0.804	0.126	0.793	0.135	0.228	0.130	0.685	0.147	0.405
1.476	3.75	0.128	0.797	0.128	0.582	0.117	0.352	0.128	0.495	0.119	0.373	0.141	0.797
1.575	4	0.120	0.863	0.118	0.695	0.109	0.475	0.120	0.575	0.111	0.837	0.134	0.762
1.673	4.25	0.110	0.568	0.108	0.295	0.099	0.527	0.110	0.888	0.101	0.704	0.125	0.399
1.772	4.5	0.098	0.489	0.097	0.708	0.087	1.020	0.099	0.313	0.090	0.602	0.113	0.450

Figure AIII-14. Tunnel 3L (Low Velocity)

Probe Height		Tunnel 3L				Tunnel 3L				Tunnel 3L			
		Position A				Position B		Position C		Position D		Position E	
		Q170T35H24R1		Q170T35H24R2		Q170T35H24R1		Q170T35H24R1		Q170T35H24R1		Q170T35H24R1	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	1.021	16.259	1.019	16.732	0.920	16.582	0.842	19.138	0.998	16.555	1.062	16.367
0.098	0.25	1.246	14.836	1.255	13.579	1.187	13.747	1.122	15.623	1.231	12.997	1.316	11.583
0.148	0.376	1.368	11.124	1.379	10.390	1.328	11.100	1.214	12.972	1.344	10.916	1.406	10.054
0.197	0.5	1.457	8.767	1.432	9.165	1.429	8.871	1.278	11.893	1.404	9.243	1.446	8.907
0.246	0.625	1.472	8.386	1.473	8.105	1.465	7.603	1.362	10.252	1.458	7.844	1.481	8.883
0.295	0.75	1.514	7.428	1.514	7.411	1.495	7.759	1.385	9.937	1.489	7.870	1.531	6.738
0.394	1	1.568	6.353	1.572	6.370	1.534	6.617	1.460	8.401	1.545	6.613	1.575	5.983
0.492	1.25	1.615	5.053	1.617	5.228	1.536	7.542	1.525	7.413	1.582	5.461	1.613	4.980
0.591	1.5	1.645	3.993	1.651	3.455	1.545	7.072	1.569	6.357	1.628	4.009	1.631	3.840
0.689	1.75	1.666	2.944	1.661	2.937	1.567	7.033	1.599	6.421	1.638	3.353	1.631	3.332
0.787	2	1.669	2.369	1.673	2.323	1.601	6.293	1.630	5.831	1.645	2.484	1.629	2.398
0.886	2.25	1.674	2.165	1.673	2.115	1.614	5.329	1.651	5.118	1.652	2.233	1.633	2.110
0.984	2.5	1.671	2.168	1.672	1.999	1.628	4.638	1.663	4.683	1.653	2.346	1.635	2.295
1.083	2.75	1.673	2.175	1.675	2.166	1.634	4.393	1.679	4.246	1.655	2.148	1.636	2.167
1.181	3	1.678	2.190	1.681	2.285	1.632	4.017	1.691	3.144	1.665	2.259	1.649	2.296
1.280	3.25	1.667	2.535	1.671	2.724	1.632	3.711	1.703	2.488	1.661	2.231	1.645	2.209
1.378	3.5	1.655	2.801	1.657	3.039	1.630	3.767	1.703	2.797	1.644	2.803	1.644	3.137
1.476	3.75	1.634	3.771	1.627	4.248	1.638	3.235	1.683	3.478	1.614	4.237	1.615	4.425
1.575	4	1.535	8.287	1.561	7.011	1.642	3.538	1.654	4.957	1.536	7.020	1.569	6.210
1.673	4.25	1.397	11.895	1.370	12.534	1.646	2.886	1.522	8.568	1.385	10.924	1.398	11.559
1.772	4.5	1.071	16.605	1.089	16.509	1.531	5.337	1.286	11.995	1.040	16.832	1.123	13.595

Figure AIII-14. (Continued). Tunnel 3L (Medium Velocity)

Probe Height		Tunnel 3L				Tunnel 3L				Tunnel 3L			
		Position A				Position B		Position C		Position D		Position E	
		Q398T35H20R1		Q398T35H20R2		Q398T35H20R1		Q398T35H20R1		Q398T35H20R1		Q398T35H20R1	
		Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.	Velocity	Turb Int.
(in)	(cm)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)	(m/s)	(%)
0.050	0.127	2.478	13.909	2.465	13.788	2.362	14.658	2.103	17.589	2.360	14.971	2.614	12.060
0.098	0.25	2.745	11.219	2.760	11.351	2.700	11.740	2.510	13.138	2.682	12.268	2.842	9.948
0.148	0.376	2.885	9.637	2.909	9.785	2.869	9.209	2.666	10.927	2.845	10.239	2.965	8.562
0.197	0.5	3.024	8.249	3.001	8.726	2.992	8.093	2.797	9.779	2.947	8.733	3.058	8.057
0.246	0.625	3.077	7.898	3.128	7.738	3.091	7.317	2.870	8.944	3.054	8.163	3.100	7.820
0.295	0.75	3.197	7.465	3.170	7.136	3.142	6.782	2.974	8.679	3.154	7.504	3.201	7.160
0.394	1	3.330	6.022	3.322	6.086	3.238	6.229	3.115	7.550	3.294	6.281	3.336	5.937
0.492	1.25	3.459	4.735	3.427	4.892	3.292	5.831	3.241	6.554	3.409	4.760	3.433	4.631
0.591	1.5	3.513	3.831	3.507	3.669	3.315	6.250	3.317	5.962	3.487	3.670	3.472	3.683
0.689	1.75	3.550	2.768	3.542	2.654	3.354	5.520	3.369	5.943	3.519	2.870	3.482	2.817
0.787	2	3.569	2.270	3.568	2.219	3.393	5.315	3.426	5.323	3.541	2.268	3.486	2.202
0.886	2.25	3.578	2.060	3.572	2.107	3.420	4.967	3.469	4.859	3.549	2.002	3.486	2.058
0.984	2.5	3.580	1.940	3.570	2.040	3.459	3.862	3.519	4.426	3.549	2.020	3.492	2.031
1.083	2.75	3.567	2.027	3.567	2.009	3.479	3.565	3.548	4.068	3.551	1.924	3.496	2.096
1.181	3	3.566	2.189	3.558	2.119	3.463	3.713	3.555	3.759	3.546	2.083	3.502	2.214
1.280	3.25	3.545	2.341	3.533	2.505	3.466	3.647	3.564	3.522	3.521	2.190	3.499	2.441
1.378	3.5	3.505	3.382	3.491	3.279	3.446	3.464	3.546	3.332	3.493	2.972	3.457	3.246
1.476	3.75	3.425	4.539	3.423	4.777	3.424	3.445	3.495	4.295	3.415	4.084	3.411	4.682
1.575	4	3.288	7.173	3.266	7.382	3.395	3.397	3.397	5.879	3.296	6.393	3.295	7.247
1.673	4.25	3.024	12.359	3.031	11.626	3.357	4.492	3.324	7.721	3.102	10.964	3.082	10.674
1.772	4.5	2.567	17.799	2.538	18.030	3.156	8.332	2.937	12.899	3.102	10.964	2.636	16.931

Figure AIII-14. (Continued). Tunnel 3L (High Velocity)